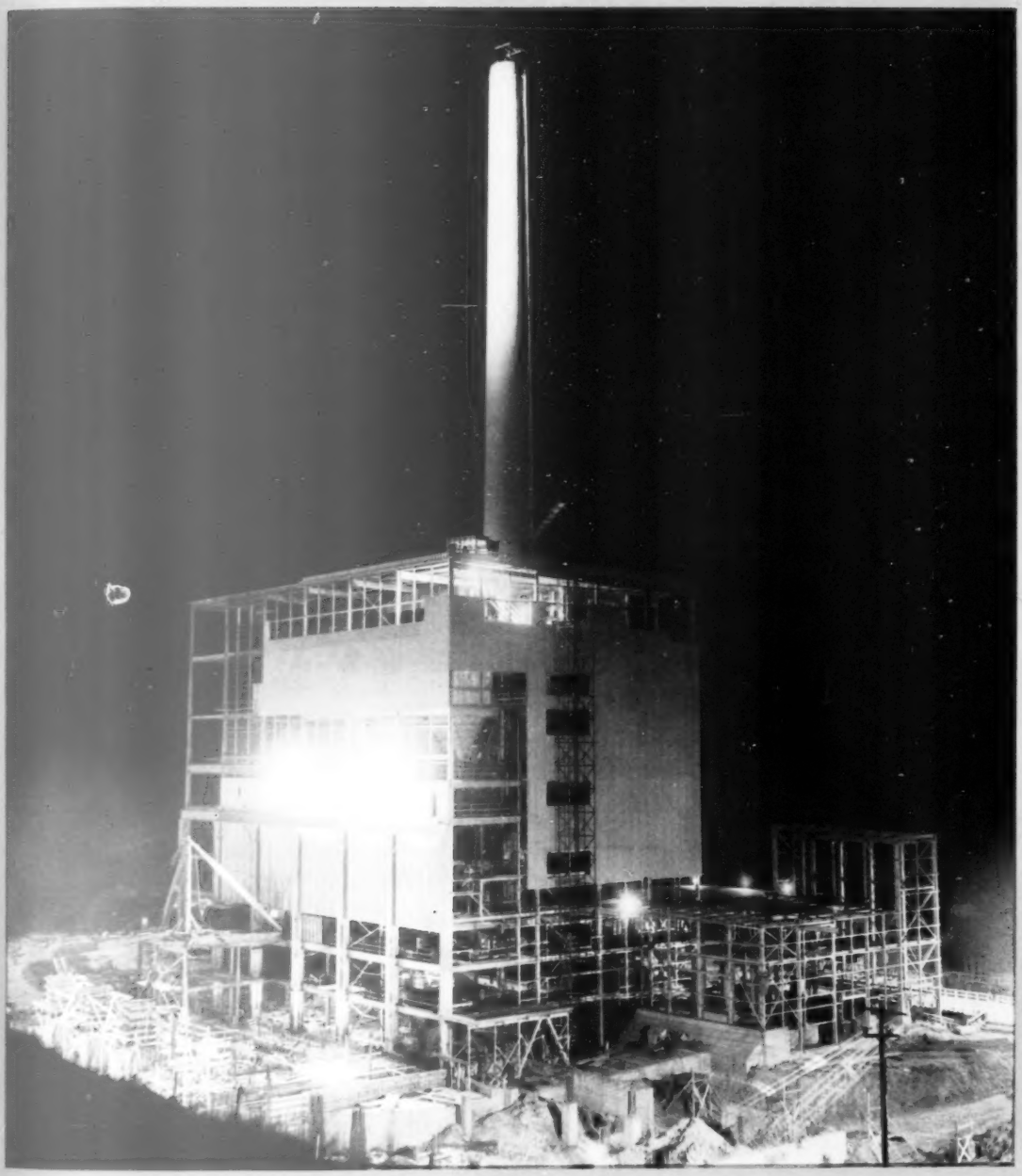
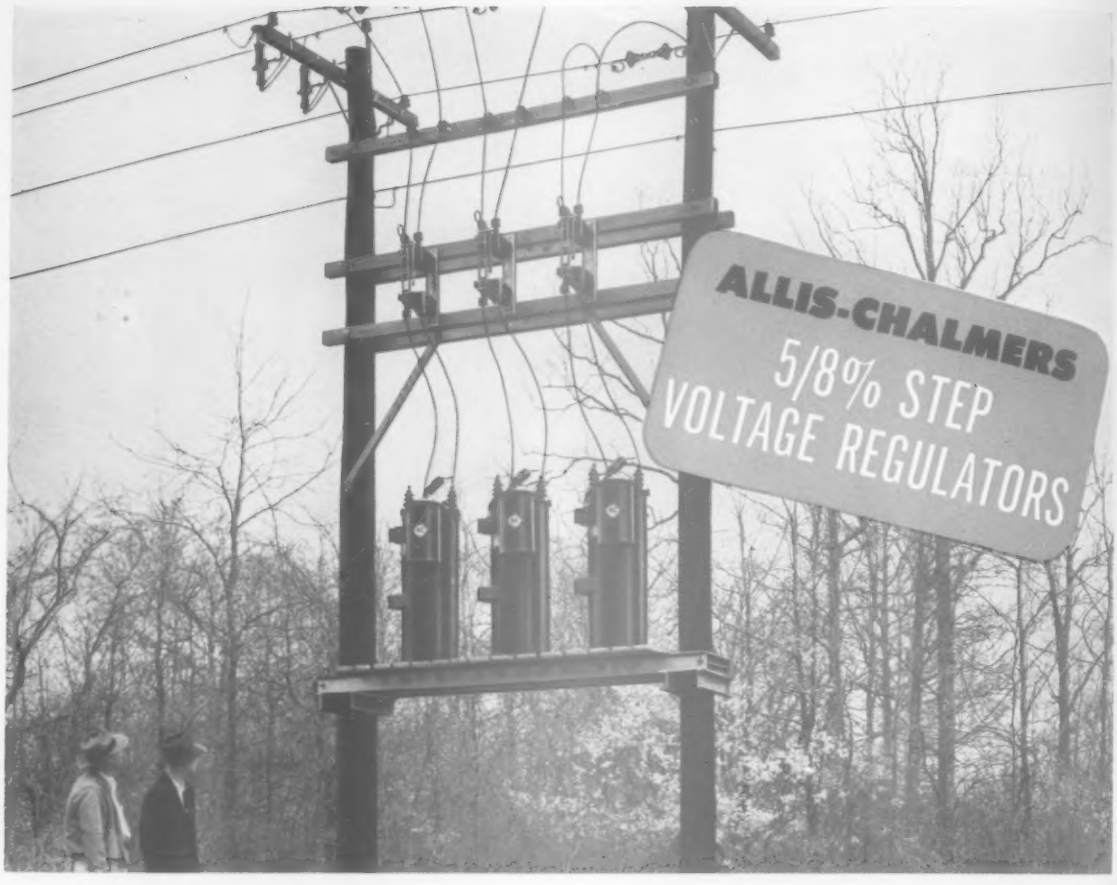
ALLIS-CHALMERS Electrical REVIEW

4TH QUARTER 1952





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Electrical REVIEW

THE COVER

NIGHT AND DAY — in the never ending quest to supply power and yet more power to meet the growing demands of America's free economy — concrete is poured, steel girders swing into place and power generating machinery is bolted into position. Symbolic of the dynamic way in which power companies have shouldered the herculean task of powering America is this photo of Wisconsin Electric Power Company's Oak Creek Station on the shore of Lake Michigan.

A-C Staff Photo by M. Durante

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HYDRAULICALLY *Stored Energy-*

New Era in Circuit Breaker Actuation

by **N. W. MORELLI**
and E. R. PERRY
Circuit Breaker Engineering Section
Allis-Chalmers Boston Works

THE OPERATION of a modern high capacity circuit breaker requires an energy storage device which will release a tremendous quantity of energy in a very short period of time. For instance, the closing operation of a typical large circuit breaker may demand as much as 130,000 inch-pounds of energy delivered during ⅛ second. This means that approximately 175 horsepower must be available instantly. Since it is not economical to provide a continuous source of power of such a value, energy storage at the location in the form of storage batteries, compressed air, or springs, has been the conventional solution. These systems have all been handicapped by the elaboration required when translating the stored energy into final mechanical motion, or by the complex methods of the original translation of energy to the bulky and often inconvenient means of storage.

With the tremendous growth of interconnected systems have come demands for doubled and redoubled breaker capacities and higher and higher reclosing speeds to maintain system stability and furnish uninterrupted power to the user.

It was with these circumstances in mind that an investigation of the use of hydraulic power in high speed prime movers for actuating circuit breakers was undertaken.

Hydraulic systems — fast and dependable

Hydraulic systems have certain characteristics which make them desirable as an actuating medium. The incompressibility of liquids permits the instantaneous transmission of power between two points much the same as a mechanical linkage. Unlike the mechanical linkage, liquids can be transmitted in all directions through tubes without loss of function or the use of bulky or complicated apparatus. Bearings and guides are unnecessary. Transformation and translation of power can be easily and simply accomplished.

The application of hydraulic power has come a long way since Pascal discovered the fundamental laws governing the action of hydraulic fluid under pressure. Hydraulic presses have been in common use for over a century. Today, no one questions the simplicity or dependability of hydraulic tool control or hydraulic brakes.

During and following the last world war, tremendous advancements were made in hydraulic equipment. Accepted average system working pressures have risen from about 1,000 psi in 1945 to as high as 5,000 psi in 1952.

New types of valves, fittings, and energy storage methods have made hydraulic systems attractive to industries which heretofore would not consider this medium. Credit for much of the development goes to the aircraft industry which in the search for perfection has brought the development of hydraulic systems in general to their present high level of acceptance. Reliability under extreme working conditions has been the major determining factor in much of their work.

Modern pneumatic operators need no apology

The modern pneumatic, spring, or solenoid-actuated circuit breaker operators are the product of many years of continuous improvement. All of these types are adequately meeting the performance requirements expected of them within their application range. Thus any new operating method must offer basic improvements in simplicity, reliability, or maintenance to meet with general acceptance. At the same time it must equal or exceed present operators in reclosing and opening speeds and provide energy storage for the standard minimum of five operations.

Hydraulic operator presented new problems

While hydraulic systems are noted for their simplicity and adaptability, the problem of designing a system to operate a circuit breaker called for the solving of three major problems:

1. A means of energy storage capable of releasing a tremendous amount of energy for a short period, yet remaining reliable and unaffected by temperature variations.
2. A hydraulic valve of simple and rugged design able to insure the repetitive high speed of operation necessary for present and future ultra-high speed power circuit breakers.
3. A hydraulic system using a small enough volume of fluid to permit reasonable velocities, while maintaining maximum efficiency and a minimum physical size of components.

In the past, a means of storing energy had always been a hindrance in the design of a pure hydraulic operating mechanism. However, the development of the pneumo-hydraulic accumulator and its subsequent widespread use has provided a very satisfactory solution to this problem. This device, illustrated in Figure 1, is one of the most efficient methods known for storing energy. To insure operation throughout the entire temperature range encountered in circuit breaker applications, a commercially available oil having a nearly flat viscosity curve was chosen as the operating medium.

If a hydraulic operator was to show any improvement in operating speed over the modern pneumatic operator, the time interval from closing coil energization to full open valve position of the main control valve had to be kept to an absolute minimum. A solenoid with sufficient force to rapidly move the large control valve would have an excessively long flux build-up time. This characteristic prevented the use of a direct-connected solenoid-operated valve. A small pilot valve, actuated by a low power, high speed solenoid and regulating the main control valve proved a satisfactory solution to this problem. This pilot arrangement not only provided high valve speeds but also allowed use of a simple, low current control circuit.

There are three variable factors which determine the needed velocity of flow: horsepower requirements, system pressure, and tube size. The horsepower for a particular breaker application is a known factor. It is obvious that the higher the pressure, the greater the horsepower per cubic inch of fluid flow. For this reason it is desirable to use as high a pressure as practical to keep the volume of oil moved to a minimum. The choice of operating pressures becomes one of economy and reliability. A pressure of 3,000 psi was found to be the most acceptable pressure to use at the present time. Hydraulic components suitable for 3,000 psi systems are standard and well proven as to reliability in service.

The tube size was determined by an oil volume and velocity relationship. In order to keep component sizes and weights down, the flow velocities used are considerably above those ordinarily employed for continuous flow application, but because of the short time intervals involved the total pressure drop in the system is less than 5 percent. All oil lines are kept as short as possible and with smooth bends where needed.

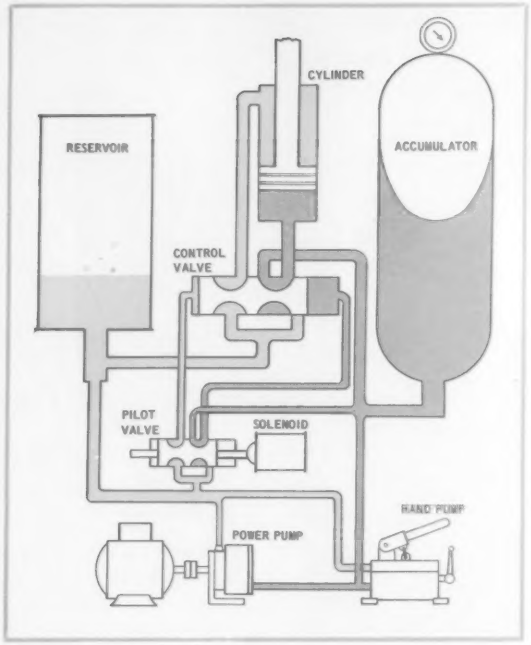
HYDRAULIC ACCUMULATOR with nitrogen-filled bladder stores hydraulic energy in seamless alloy steel bottle. One of the most efficient energy storage devices known, it retains energy indefinitely. When put in service the Neoprene bladder is filled with nitrogen, expanding to fill the entire area. Poppet valve prevents extrusion of the bladder. Oil is pumped into the tank, compressing the bladder. Since oil and gas pressures are always equal, only stress on bladder walls is compression. Accumulator service records of over a million flexations are on record. **(FIGURE 1)**

Operating sequence is simple

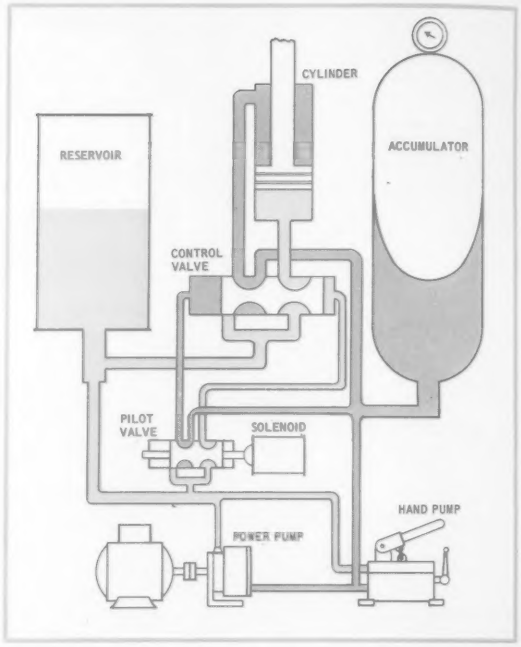
The flow of oil and the action of the circuit is illustrated in Figures 2a and 2b. Normally the ram is at the lower limit of its travel and both valves are to the right. Energizing the solenoid snaps the pilot valve spool to the left and allows oil from the accumulator to surge into the right-hand chamber of the control valve, forcing that spool to the left so that high pressure oil rushes in under the piston of the cylinder, driving the ram upward to close the breaker.

As the ram closes the breaker, it trips a limit switch opening the solenoid circuit. A spring contained in the solenoid instantly returns the pilot valve spool to the right and high pressure oil surges through the pilot valve into the left chamber of the control valve, forcing the control valve spool back to the right and allowing oil from the accumulator to rush in above the piston, driving it back to the original position to complete the cycle.

On the upward stroke oil above the piston, and on the downward stroke oil under the piston, is exhausted through the control valve to the reservoir at atmospheric pressure. The oil in the chamber of the control valve toward which the spool moves is exhausted through the pilot valve to



SIMPLIFIED DIAGRAMS of hydraulic circuit show the nine essential elements in the system, and valve positions during closing stroke (left) and as ram is returning from closing stroke (right). **(FIGS. 2A and 2B)**



RESERVOIR at top means pump has no chance to lose prime. Latch (not shown) on pilot valve enables maintenance man to use hand pump as positioning jack. Low pressure in color, high pressure in gray.

the reservoir also. The reservoir contains a baffle arrangement to reduce the aeration of the oil. Since the reservoir is at atmospheric pressure, there is no pressure build-up to cause valves or ram to creep. The gravity fed power pump automatically maintains pressure in the high pressure and accumulator circuit within the operating range.

This new hydraulic system offers several basic improvements over present-day methods. Coupled to a full mechanically trip-free linkage as shown in Figures 3 and 4, the unit provides high speed multiple repetitive reclosing.

Full speed emergency closing provided

An additional advantage of the hydraulic actuating system is the simple way in which emergency manual closing can be obtained. On occasions, it is desirable to close the breaker when there is no control circuit or power source for the power operated pump. A hand operated pump allows the operator to store enough energy for one or more closing operations in the accumulator. Enough energy for one operation can be stored by use of the hand pump in less than a minute.

Once the accumulator has been charged with the hand pump, the breaker can then be operated from the control board or by hand. It will then close at full speed, an advantage particularly desirable in emergency. The hand pump has an integral reservoir which has reserve oil storage for one operation.

Pump doubles as jack for positioning

The same hand pump used for emergency closing can also be used as a maintenance closing device. To close the breaker, the pilot valve is latched in the closed position (to the right). The hydraulic mechanism now acts as a simple hydraulic jack and the breaker can be slowly jacked closed or to any intermediate position. Check valves within the hand pump lock the circuit breaker positively in any position, affording maximum safety to inspection or maintenance personnel. The hand pump has a built-in manually operated release valve for releasing pressure from under the piston at a controlled rate of flow to the reservoir. The circuit breaker tailspring furnishes power to force the piston downward.

Maintenance is minimized

The new hydraulic actuator offers several important advantages over other modern actuating systems:

1. ***Maintenance*** is reduced to a minimum by virtue of the few moving parts employed. The entire system contains but one adjustment and this is readily accessible. All moving parts within the system are constantly immersed in oil having excellent lubricating properties so wear between sliding surfaces is minimized. The completely sealed circuit protects all internal surfaces from corrosive effects of moisture and dirt.

2. ***High reclosing speeds*** — The hydraulic actuating system provides high speeds of operation when needed. Reclosing speeds far in excess of those presently required by circuit breaker standards are easily obtained.

3. ***High system efficiency*** — The high efficiency of the hydraulic system reduces pump motor size well below that of a pneumatic system of the same capacity. The

pump-up time from zero to full pressure is about 25 percent of the time required with a pneumatic operator.

High speed films record tests

A thorough test program was conducted to determine the operating characteristics of the hydraulic actuating system. A recording oscillograph in conjunction with strain gages was used to determine pressure drop and pressure waves in all major parts of the system. Simultaneously, valve and solenoid times were recorded on the same strips of film.

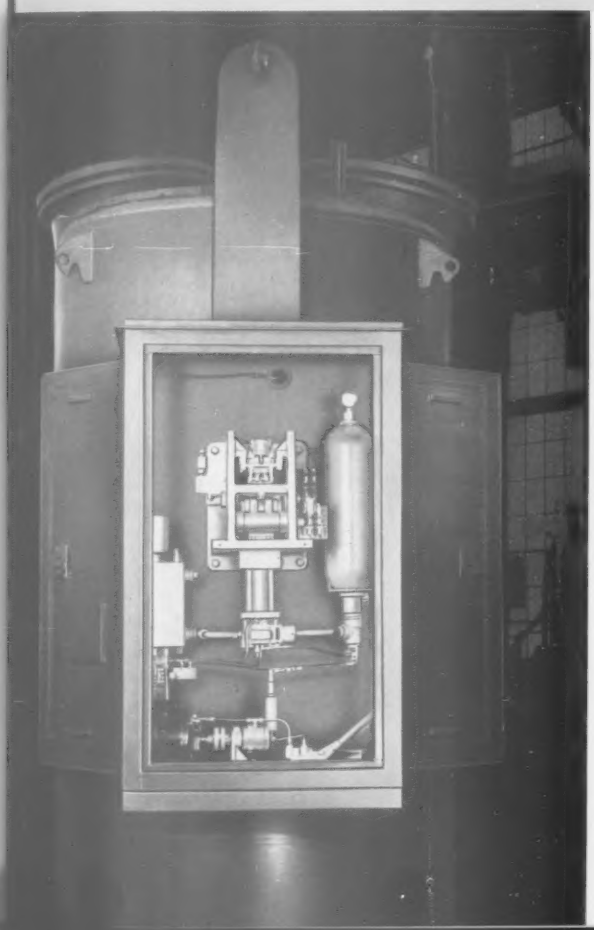
Synchronized with the recording oscillograph, a high speed movie camera (500-3,000 frames per second) was utilized to record the movement of the ram and toggle mechanism. This coordination provided an accurate means of calculating the rate of fluid flow and corresponding pressure drop between any two points.

Closing and reclosing operations were made on one test unit at 50 psi pressure intervals from maximum to minimum pressure to determine the variation of operating characteristics.

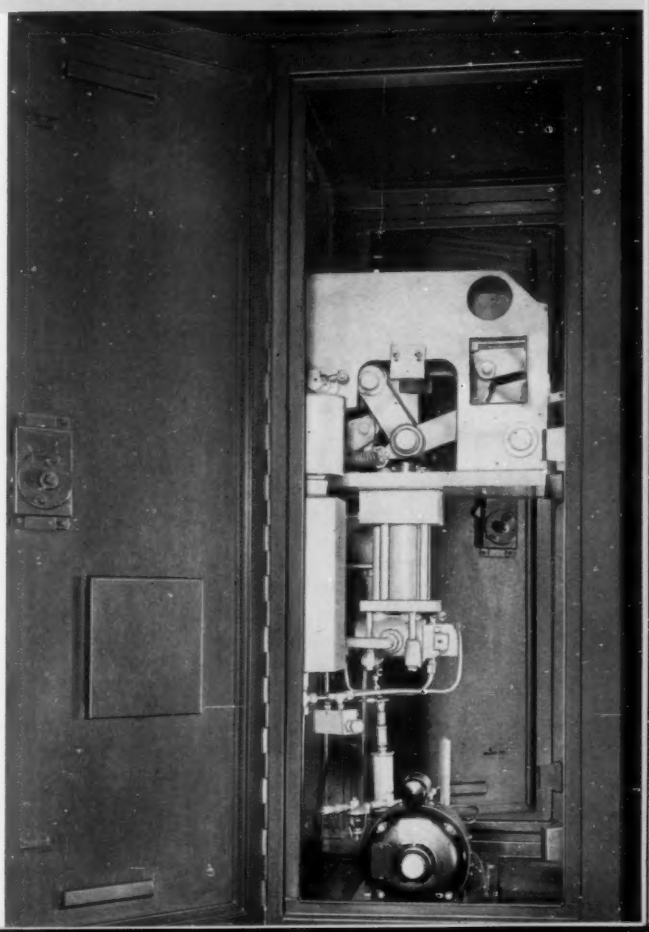
Early tests indicated that the hydraulic actuating system could attain very high reclosing speeds. When coupled with a toggle linkage, as test models have been, it was found very important that the ram be rapidly retrieved from its upward position during repetitive reclosures. This is necessary to allow the mechanical trip-free mechanism to reset quickly and permit the next reclosure. The ram return time was found to be directly controlled by the valve shift time, while valve speed is approximately proportional to the operating pressure. Oscillograms show that pressure is instantaneously applied to the actuating ram immediately after the valve starts to open. There is essentially no time lost waiting for a force or pressure to reach a maximum as is the case with other circuit breaker actuating means.

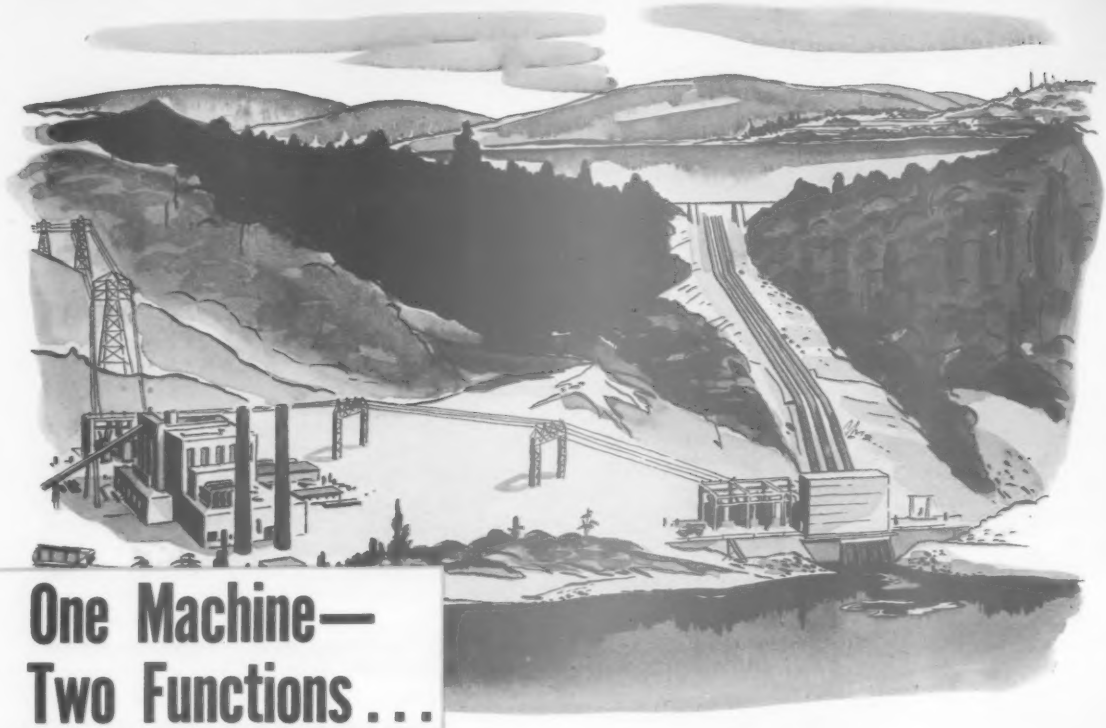
The hydraulic actuating system described here promises to be the forerunner of a new era in circuit breaker design. Mechanical linkages may conceivably be replaced with tubes carrying an operating fluid. The physical design of power circuit breakers, as presently known, can be altered considerably. The size and complexity of controls can be reduced. Like all other engineering advancements, the full importance of the effects of hydraulic actuation upon the design of power circuit breakers will not be fully realized until each individual design change has been tried and proven in the field.

EXPERIMENTAL ACTUATOR adapted for use with mechanically trip-free operator. Pilot and control valves are bolted together and connected to base of ram cylinder, minimizing friction losses and tubing. Since operating pressure is high, total volume of oil is small and neither reservoir nor accumulator need be large. **(FIGURE 3)**



VIEWED FROM LEFT side, simplicity of hydraulic operator is apparent. Only a few small lines and standard fittings connect all elements. Low energy solenoid at center controls system. Pressure gauge at top of accumulator provides instant check on system pressure. Control panel has been removed in both views. **(FIGURE 4)**





One Machine— Two Functions . . .

New Reversible Pump-Turbine

by **FRANK E. JASKI**
Asst. Chief Engineer
Hydraulic Section
Allis-Chalmers Mfg. Co.

This new machine uses water power to generate electricity during peak load periods, pumps water back for future use during off-load periods.

THE FLAT IRON POWER and Pumping Plant is one of a series of power plants being built by the Bureau of Reclamation in Colorado on the eastern side of the Continental Divide as a part of the Colorado Big Thompson Project. The primary purpose of this project is to augment the present inadequate irrigation supply on the eastern slope of the Continental Divide in northeastern Colorado by bringing water from the headwaters of the Colorado River on the western slope through the Alva B. Adams Tunnel.

This diversion project will comprise 13 reservoirs, 23 dams and dikes, and 5 hydro-electric plants connected by 8 tunnels, 2 siphons, 10 canals, and 3 pumping plants — all located within the State of Colorado.

Flat Iron Power and Pumping Plant is located in Chimney Hollow, approximately 10 miles west of Loveland, Colorado. This is a peak load plant for the power system and will contain 2 high head Francis turbines each rated 48,000 hp under 1055-ft head. It will also contain a 12,000-hp reversible pump-turbine, driven by a 10,000-kw motor (generator).

This pump-turbine is the newest product in the hydraulic turbine field to be introduced in this country. It was developed to provide the hydro-electric field with a more compact unit for pumped storage of hydro-power. Its design is the result of combining long years of experience in building both hydraulic turbines and centrifugal pumps.

Stores hydro-power

The function of this unit is to provide stored hydro-power by pumping water from a suction pond at a lower elevation to a storage lake at a higher elevation. The pump-turbine can then utilize this potential energy by developing power as a hydraulic turbine when the flow is reversed through the unit and passes from the storage lake to the suction pool. Rotation is in one direction when operating as a pump, and in the opposite direction when operating as a turbine. It is a vertical unit similar to a Francis turbine having a conventional spiral case and draft tube. The pump-turbine is direct-connected to an electrical machine which serves as a motor when the unit operates as a pump, and as a generator when the unit operates as a turbine.

In pump storage applications, pumping is done during periods of low load demand, or during off-peak periods when the power costs very little. Power is generated during peak load periods when it can be sold at a much higher rate. In this manner, pumped storage can be economical and in proper application can be made self-liquidating and profitable.

The Flat Iron pump-turbine will be used for pumped storage, although it was primarily intended for use as an irrigation pump. It will pump water from the tailrace of the Flat Iron Power Plant to Carter Lake Reservoir. Water will be transported to the bottom of Carter Lake through an 8-ft steel penstock and pressure tunnel system 1.1 miles long. A butterfly valve at each end of the system will permit unwatering and maintenance.

When used as a pump, the pump-turbine will deliver 370 cubic feet per second against a head of 240 feet. As a turbine it will develop 12,000 hp under a 290-ft head. The pumping head will vary from 170 to 300 feet, and the turbine head will vary from 290 to 140 feet.

The pump-turbine is not intended for regulating load and will not have movable wicket gates or a governor. When starting as a turbine, the unit will be synchronized by means of a butterfly valve.

First, the valve will be opened a small amount. This will admit sufficient water to bring the unit up to about 95 percent of normal speed. Then, by opening a by-pass valve the speed will come up to normal and the unit can be put on the line. Following this, the butterfly valve will be opened to its full opening and the generator output will correspond to the head existing at that time.

Another method of synchronizing will be starting up with the butterfly valve to about 200 rpm, and motoring the unit on the line up to synchronous speed, then switching to generating and opening the butterfly valve wide open to develop full power.

Operates at two speeds

Two-speed operation is a novel feature of this unit. Normally, it will operate at 300 rpm for pumping and at 257 rpm for generating power. While it can operate as a generator at either 300 rpm or 257 rpm, depending upon which system of poles is cut into the circuit, it will develop considerably more horsepower and a better over-all efficiency at 257 rpm. Similarly, best over-all pumping efficiency is obtained at 300 rpm.

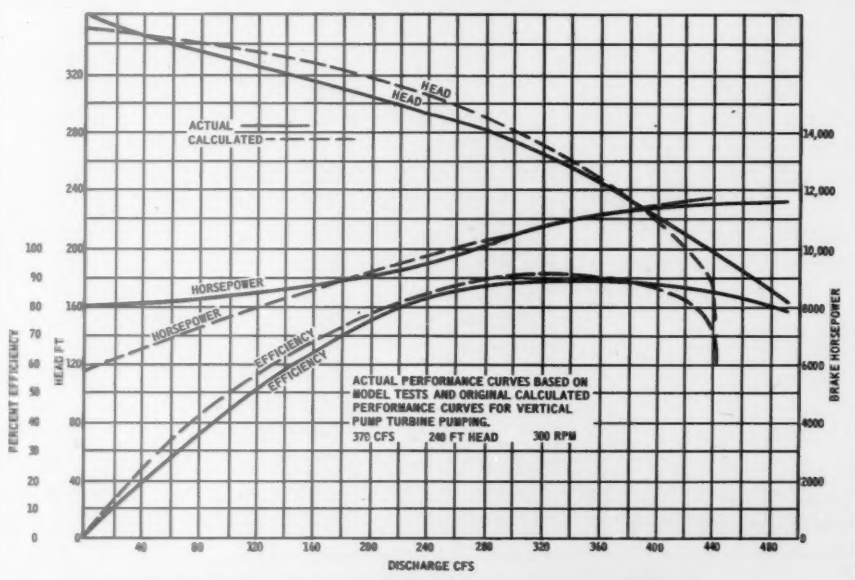
When started up as a pump at 300 rpm, the butterfly valve will be closed and the motor will supply the shut-off horsepower of about 8000 hp. As soon as pressure builds up in the casing, the valve will be opened and water will be carried up the penstock to Carter Lake. The valve will then be opened wide open and pumping will proceed from the minimum head of 170 feet to a maximum head of 300 feet. At the end of the pumping cycle the pump will be shut down until the next generating period, or pumping period if used only for irrigation.

Pumping performance

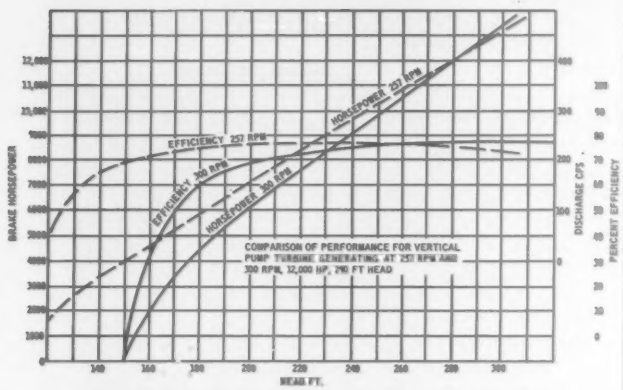
For laboratory test purposes, a scale model was built having a ratio of 1/5.26 to the larger unit. Figure 1 shows the performance curves for pumping. The head and horsepower are stepped up from the model test, while the efficiency shown is that obtained on the model. It is expected that the efficiency will be one to two percent better on the large unit. It will be noted that the maximum horsepower required from the motor will be about 11,500. The maximum shut-off head with the butterfly valve closed will be 360 feet.

Turbine performance

Figure 2 shows the performance curves for turbine operation at 300 rpm and 257 rpm. It will be noted that the horsepower is 12,600 at 290 feet head for either speed. However, as the head goes down, the horsepower output



AS A PUMP, these performance characteristics were obtained. **(FIGURE 1)**


BRAKE HORSEPOWER
DISCHARGE CFS
PERCENT EFFICIENCY
HEAD FT.
EFFICIENCY 257 RPM
EFFICIENCY 300 RPM
HORSEPOWER 257 RPM
HORSEPOWER 300 RPM
COMPARISON OF PERFORMANCE FOR VERTICAL PUMP TURBINE GENERATING AT 257 RPM AND 300 RPM, 12,000 HP, 290 FT HEAD

AS A TURBINE, efficiency and horsepower ratings obtained at the two operating speeds are compared in these curves. **(FIGURE 2)**

is considerably higher at 257 rpm than at 300 rpm. For example, at the minimum head of 140 feet, the output would be zero at 300 rpm, while at 257 rpm it would still be about 3400 hp. Again in this figure, the horsepower was stepped up from the model test, but efficiency shown is the efficiency obtained in the model test. The efficiency curve at 300 rpm drops quite steeply with reduction in head, while at 257 rpm it is very *flat*. At 140 feet where the efficiency is zero at 300 rpm it is still 75 percent at 257 rpm. It is expected that the efficiency of the larger unit will be one to two percent higher than these model efficiencies.

Special construction for dual function

Because of its dual function, the pump-turbine was developed as a two-speed unit so that it can be operated at the proper rpm for best over-all efficiency when pumping as well as when generating power. Figure 3 shows a cross-section drawing of the unit. The runner will be made of bronze. The spiral case of welded steel plate will be in one piece. The elbow type draft tube will be made of concrete and will have a steel plate liner in the top portion.

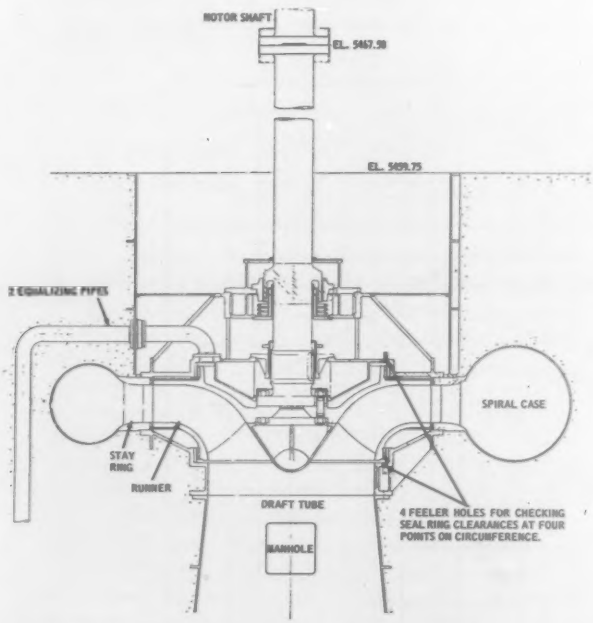
A generator-type main bearing with a babbitted bearing shell arranged for oil lubrication will be used. Spiral grooves inclined upward to left and right will circulate the oil through the bearing regardless of the direction in which the unit is running. Two 5-inch equalizer pipes leading from the cover plate to the draft tube will relieve the pressure at the top of the runner and reduce the downward thrust.

The runner will be submerged below the level in the tailrace so that the pump will be primed at all times, ready to start pumping. Ampco bronze wearing rings will be provided on the runner, and stationary seal rings of a different composition will be provided on the upper and lower cover plates. The main shaft will have a stainless-steel sleeve in the packing box where it passes through the upper cover plate.

Provision will be made for unwatering the unit with compressed air if it is desired to start the unit with reduced torque.

Model tests indicate performance details

Exhaustive tests were made in the hydraulic laboratory. Figure 4 shows the arrangement that was used. To measure flow, a Venturi meter was placed in the hydraulic circuit and turned end for end to determine flow in either direction. The pump at one end of the loop was used to produce the head for turbine operation and was removed during the pump test of the model. Cavitation tests were



THIS CROSS-SECTION indicates construction of the Flatiron pump-turbine. **(FIGURE 3)**

PUMP-TURBINE and butterfly valve tests were made on this setup. Note valve lever and dial in upper left corner. **(FIGURE 4)**

performed both for pumping and turbine operation to obtain the critical sigma for breakdown in head for pumping, and breakdown in horsepower for turbine operation.

Complete investigations of pressure distribution between the runner and stay ring around the entire circumference were made while pumping. Similar investigations were made of the pressure distribution at the top of the draft tube and at the casing nozzle. The pump model operated very quietly and smoothly over the entire range of operating heads.

A series of stay rings were tested to determine the most effective stay vane shape. The large stay ring will be cast steel.

Investigations were made of the flow through the butterfly valve at various positions of the valve wicket. The valve also operated very smoothly and quietly in all positions during the model tests.

Figure 5 shows a close-up of the model from the top cover plate side. A hydraulic dynamometer was used to obtain the output of the turbine.

Runaway speed within safe limits

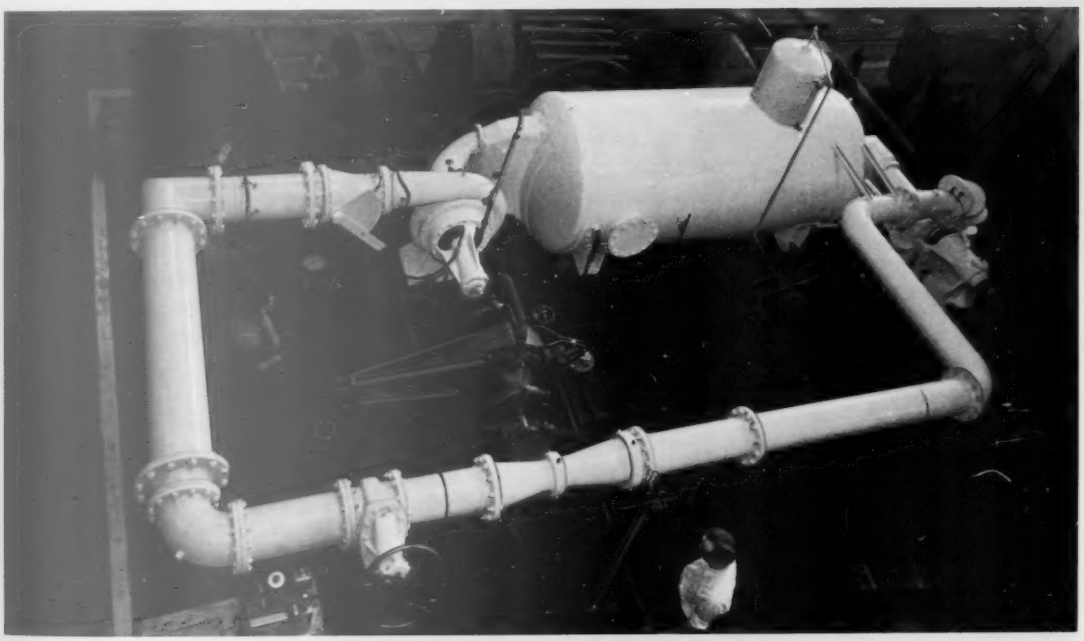
In the event that the unit should lose its load when running as a turbine, it may reach its full runaway speed. However, this will be only 430 rpm at the maximum head of 290 feet. Both pump-turbine and generator (motor) will safely operate at this speed. Overspeed switches will be provided to shut the unit down by closing the butterfly valve.

Pump-turbines like the Flat Iron unit can be built either with or without wicket gates. Of course, if a governor is furnished the unit can also be used for variable or regulating load at a constant head if it is found economical, and if the storage pond capacity is sufficient to maintain a constant head.

The Flat Iron pump-turbine is scheduled to go into operation in 1953 and will be the first unit of this type in the United States. Applications of pump turbines for pumped storage power are becoming more numerous in the United States and abroad.

For example, two pump turbines are now being built for the Pedreira Pumping Plant of the São Paulo Light and Power Company in Brazil, and one unit for the Edgar de Souza Plant. Model tests of these units were also made in the hydraulic laboratory. They have movable wicket gates controlled by a governor. Each Pedreira unit is rated 19,000 hp under 89-ft head as a turbine. For pumping, each is rated 1800 cfs against a head of 78 feet. These units will operate at a speed of 150 rpm for both pumping and turbine operation. The rating for the Edgar de Souza pump-turbine is 1800 cfs at 78 feet for pumping, and 15,900 hp at 80-ft head for turbine operation — both at 150 rpm. The largest pump-turbine in the world will be built for the TVA's Hiwassee Plant in North Carolina. It will have a rated capacity for pumping of 3900 cfs against a head of 205 feet requiring a motor of 102,000 hp at 106 rpm. As a turbine it will be rated 80,000 hp under 190 ft net head with maximum output up to 120,000 hp at 240 ft. Reversible pump-turbines can be supplied for heads from 40 to 1,000 feet and in capacities up to 100,000 hp and more.

It is expected that more and more units of this type will come into use within the coming years and that they will soon prove to be very economical for supplementing much needed peak load power for the over-taxed power systems where conventional type hydraulic turbines cannot be used.



THIS MODEL TEST ASSEMBLY was used to obtain all performance data for figuring efficiencies of the Flatiron unit. **(FIGURE 5)**

PROTECTIVE DEVICES IN UNIT SUBSTATIONS

Protect Motors From Surges

by **B. M. KLEINMAN**
Substation Section
Allis-Chalmers Mfg. Co.

TYPICAL of unit substations used to power motors from overhead lines is this 1500-kva MCS substation.

Here's how you can modify the steep wave fronts of lightning and transient surges entering from overhead lines.

WHEN MOTORS are directly connected to exposed overhead lines, accepted practice requires some means of protecting them from lightning surges. Even when connected to overhead lines through a transformer or a substation, motors may need surge protection because transformers can transmit surges of sufficient magnitude to damage motor insulation.

Present-day liquid-filled power transformers have a relatively high basic insulation level. They can be protected from surges by lightning arresters on the overhead incoming line. High voltage metal-clad switchgear has a lower impulse level than liquid-filled transformers. However, switchgear has sufficient spacing between parts of different potentials so that no additional surge protection is necessary if it is connected to overhead lines through a power transformer, and the feeders leaving the switchgear are underground cable runs. On the other hand, space limitations as well as limitations of dry-type insulation make it difficult to incorporate high impulse strength in the windings of a rotating machine.

There are two major problems to be dealt with in the surge protection of an ac rotating machine. First, insulation from line to ground, called major insulation, must be protected. Second, insulation between adjacent turns on the coils, called turn insulation, must be protected.

Major insulation must be protected

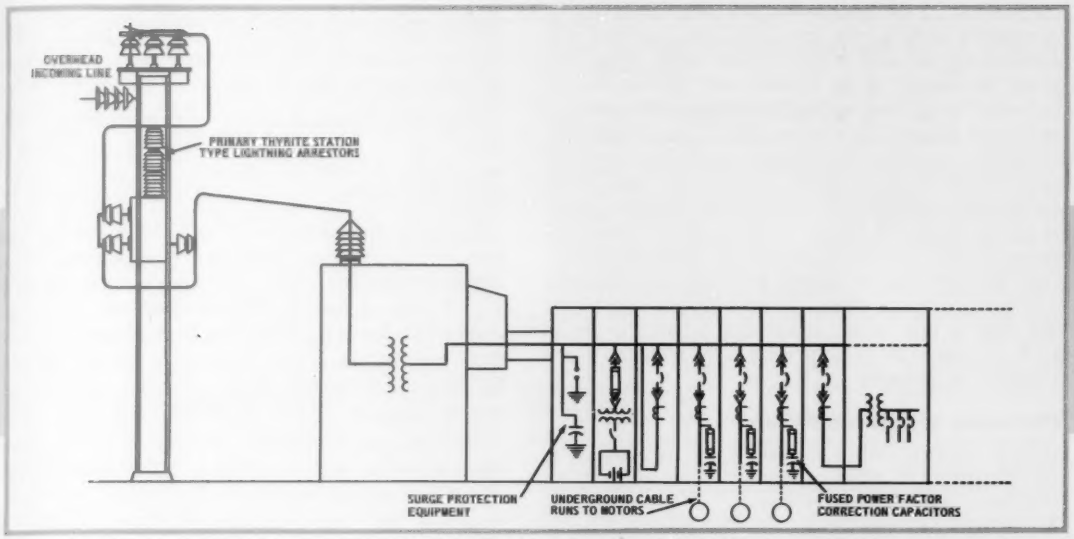
While transformers, switchgear, and similar apparatus is considered to have an impulse ratio (the ratio of the crest value of the maximum impulse voltage to the crest value of the one-minute high potential test voltage) in the general order of two or more, rotating machines are considered at present to have an impulse ratio only slightly greater than unity.

When more complete information is available on rotating machines, it may be found that the impulse ratio is considerably larger than unity, but until such data is available the crest value of the motor's one-minute high potential test voltage should be considered the maximum impulse voltage allowable on the major insulation.

The one-minute high potential test voltage for rotating machines is twice rated voltage plus 1000 volts. Therefore, when dealing with machines connected to metal-clad switchgear which is rated 15 kv or less, as would be the case in unit-type substation installations as diagrammed in Figure 1, incoming surges must be limited to approximately 2.1 times the crest of the rated 60-cycle motor voltage if major insulation is to be adequately protected.

Turn insulation affected by wave front

The development of turn insulation of machines has been based mainly on operating experience. Under normal conditions, the turn insulation is subjected to relatively low voltages, ranging from 1 to 400 volts. But when a steep wave surge voltage enters the winding, 100 to 1000 times normal voltage may be impressed across the turns.


OVERHEAD INCOMING LINE
PRIMARY THYRITE STATION TYPE LIGHTNING ARRESTORS
SURGE PROTECTION EQUIPMENT
UNDERGROUND CABLE RUNS TO MOTORS
FUSED POWER FACTOR CORRECTION CAPACITORS

LOCATION of surge protection in a unit substation is indicated by this diagram. **(FIGURE 1)**

This very high voltage between adjacent turns may be explained by referring to Figure 2, which illustrates a steep wave front surge approaching a machine's windings. When it enters the winding, a small but definite time is required for the voltage wave to travel from a point on the first turn to an adjacent point on the next coil. Contrary to common belief, the wave does not necessarily travel the complete length of the turn because of capacitive coupling between turns. Nevertheless, some time is required for the wave to travel from one point on the coil to another. The time interval for a wave to travel from the first turn to the second is represented by *L* in Figure 2.

If the wave is steep enough and the magnitude *V* is large enough, the first turn of the winding will be raised to high potential *V'* before the surge has time to reach the second turn. Consequently, full potential *V'* is imposed across the insulation between the first and second turns.

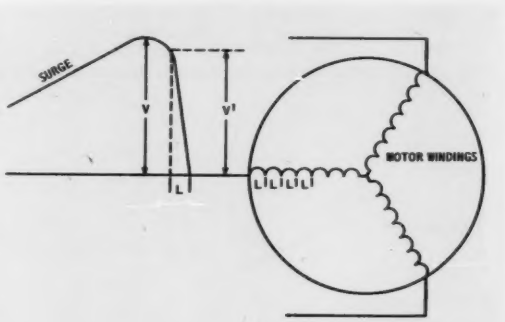
Insulating armature coil turns to withstand these steep wave voltages is not economical. A more feasible solution is to retain present insulation standards and apply protective measures.

Transformer connections affect surge peaks

Surges are transmitted through transformers by both electrostatic and electromagnetic couplings. The electromagnetic transfer depends upon the turn ratio, short circuit reactance, the kva of the transformer, and the bank connection. It is not appreciably affected by the construction of the transformer or by the constants of the low voltage circuit. The magnitude and steepness of surges transmitted by the electrostatic coupling varies greatly with construction of the transformer and the components of the low voltage circuit.

Surge magnitude that can be transmitted electromagnetically through transformers can be obtained from Figures 3, 4, and 5. These curves apply to transformers with turn ratios of four to one or higher; transformers with turn ratios below four to one afford even better protection. Each graph represents a particular type of transformer connection. The body of each graph is made up of a family of curves, only two of which are shown. The lower limit curve represents a 300-kva transformer, while a 90,000-kva transformer curve is the upper limit. To determine the approximate surge crest voltage through use of these graphs, four things must be known: (1) transformer bank connection; (2) transformer kva; (3) rated voltage of the motor; and (4) whether primary arresters on the transformer are for a grounded or ungrounded system.

With this information at hand, select the appropriate graph for the transformer bank connection. Then estimate where, between the extremes shown, the curve represent-



SURGE VOLTAGE DIFFERENTIAL between adjacent turns of a motor's windings reaches potential V^1 in time L required for surge to pass through one turn. **(FIGURE 2)**

ing the kva of the transformer will fall. The point of intersection between the kva curve and a vertical line representing the rated voltage of the motor, when projected horizontally to the ordinate, will indicate the approximate surge crest voltage in multiples of machine rated crest voltage. From these graphs it can be seen that surges of magnitude high enough to damage a motor's major insulation can result in either of two cases: if the transformers involved have an extremely large kva rating, or if the banks are wye-wye connected. If dangerous surges through a particular transformer bank are possible, then an investigation should be made to determine whether a lightning arrester is available that can reduce this surge to safe limits. If lightning arresters are to be used, it is preferable to locate them at the terminals of the motor to be protected.

Protection of turn insulation

Only in extreme cases is it possible for transformers to transmit surges of sufficient magnitude to damage major insulation. However, the turn insulation of a motor may be damaged by surges having small magnitudes, even in the order of the motor's rated voltage, if the wave front is steep enough. Protection from steep wave front surges which a transformer may transmit by means of electrostatic coupling should be provided.

Turn insulation can be protected by placing capacitors to ground on the machine feeder. If lumped capacitance C is inserted, preferably at the machine terminals as illustrated in Figure 6, the capacitance will be charged through the surge impedance of the line by all waves arriving over the line. The charging rate will depend upon the crest value of the incoming wave, the surge impedances of the line, machine characteristics, and also upon the value of capacitance in microfarads.

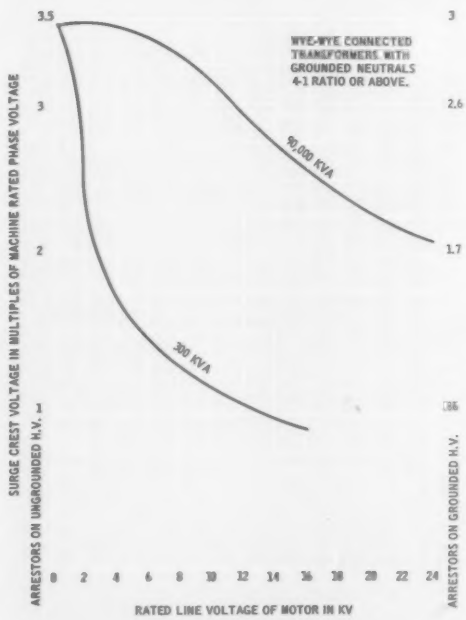
This surge capacitor changes the wave shape of the surge from its original form *a* to form *b*. This change in wave shape reduces the voltage applied across the turn insulation from the high value of V' to the smaller V''.

Knowing the characteristics of both the machine and line, it is possible to determine the maximum rate of change or steepness which can be impressed on the winding. A study of many installations indicates that in general a minimum of 0.25 microfarad placed at the machine, and a limit placed on the magnitude of the applied wave, by lightning arresters if necessary, offers sufficient protection to prevent excessive turn stresses.

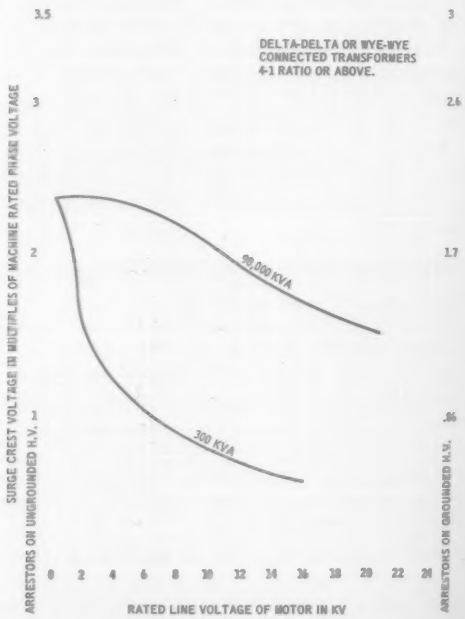
This does not establish the total amount of capacitance which should be used. For reasons discussed later, a larger capacitance may be required.

In any case, care must be taken when applying capacitors to a circuit. Resonance between the protective capacitor and transformer or circuit inductance may build up large voltages in case of switching or other oscillatory transients. To protect against this, an arrester on the transformer secondary will play a double role: It protects against the small possibility of large surges coming through the transformer; and when capacitance is added for surge protection, it also protects against any voltage build-up by a resonant circuit.

TRANSFORMER CONNECTIONS determine the magnitude of surges that can be transmitted to switchgear and motor feeders electromagnetically by substation transformers. **(FIGURE 3)**



USE THESE GRAPHS to estimate peak surges. Consider the curves shown on the appropriate graph as two in a family of curves having nearly linear relationship to each other. **(FIGURE 4)**



Machine connections influence protection needs

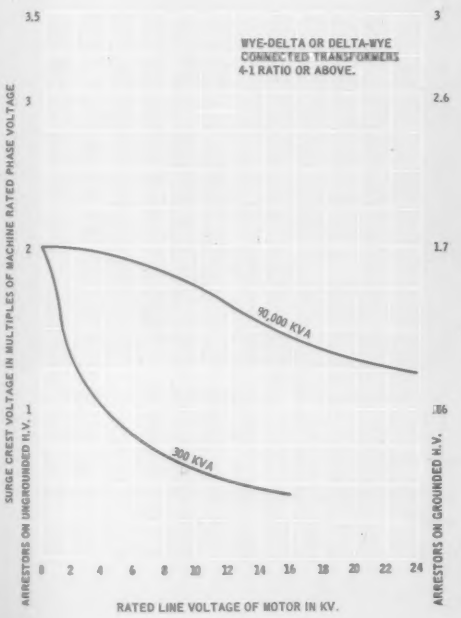
Protection of machines with solidly grounded neutrals presents no further problem, since surges are reflected negatively (with change of sign) at the solidly grounded neutral, and the voltage within the winding will be less than the applied surge.

Surge protection of ungrounded wye-connected or delta-connected machines is more difficult. Voltage waves which enter the winding reflect positively (without change of sign) at the neutral of an ungrounded wye-connected machine, and double voltage may be obtained. If the machine is delta-connected, double voltage may be obtained at the middle of the winding for equal surges on the two lines.

In addition to the problem of reflections in ungrounded machines, the lightning arrester characteristics should also be considered. Lightning arresters for use on an ungrounded system have a higher breakdown voltage than arresters for a grounded system of the same voltage rating, because the voltage at which the arrester ceases to conduct current must be higher for the ungrounded system. Since grounded machines will generally be used on a grounded system and ungrounded machines on ungrounded systems, the ungrounded machines will be subjected to higher surge voltages. See Figure 7.

Reflection at the neutral point of an ungrounded machine is dependent upon the rate of rise, or steepness, of the surge entering the machine. In order to reduce high voltages caused by reflections, the rate of rise is normally held to one-half of that which would be allowed on a similar grounded machine. The rate of rise may be reduced by using a larger capacitance in the order of 0.5 microfarads.

SKETCH A CURVE representing your unit's kva. Pick out the point of intersection with a line representing rated motor line voltage to determine peak surge on unprotected motor. **(FIGURE 5)**



Location of surge protection

Often the question arises as to how far away from the machines the protective equipment may be placed without affecting the protection. The preferred location is at machine terminals. If this is not possible because the motors are operating in an explosive atmosphere, or if for economical reasons it is decided to provide protective equipment at only one point on a common bus to safeguard several machines, then proper grounding becomes increasingly important. If lightning arresters are used, a common low resistance grounding system should be used for the protective equipment and the machine frames.

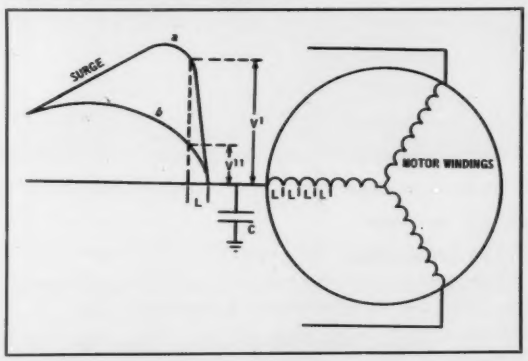
While the location of protective equipment on a common bus gives adequate protection against surges coming in through the overhead line, it does not protect against surges originating in the feeders. Field tests have shown that the sudden application of full rated voltage to the terminals of a rotating machine results in transient voltages across the line terminal coils. These transient voltages are frequently in the order of applied line-to-neutral voltage. The magnitude depends upon the point on the normal frequency voltage wave at which the circuit breaker first makes contact — the maximum being obtained when the breaker is closed at the crest of the wave.

These transients are approximately equal to normal line-to-neutral voltage so they are of no consequence to the major insulation; but they have a very steep wave shape and must be considered in order to protect turn insulation.

Damage caused by these transients is apparently cumulative. A machine may be exposed to them many times before failure occurs. The number of times a machine is subjected to these voltages is proportional to the number of times it is started.

On applications where the machines are started frequently, it is considered good practice to protect the insulation of rotating machines with external protective devices.

VOLTAGE DIFFERENTIAL between adjacent turns is reduced from high peak potential V^1 to lower V^{11} by adding capacitor C which flattens surge wave front. **(FIGURE 6)**



Selecting the protective device

The type of device needed to protect against these switching transients can be determined by considering the functions of the two most commonly used protective devices: lightning arresters and shunt capacitors.

The lightning arrester is essentially a voltage reducing device. As such, it is effective in limiting the crest value of the transient voltages but has little or no effect on the wave front. The arrester gap must be set to operate at above normal voltage, otherwise it will functon continuously. Consequently, the arrester will not function on switching transients unless they exceed the spark potential of the arrester.

The capacitor, on the other hand, is a surge-absorbing device. Because of this property, it can alter the steep-wave front of the switching transients which overstress turn insulation. To be effective, the capacitor must be located between the machine and the switch. Theoretical studies and tests indicate that a capacitance of the order of 0.1 microfarad as a minimum between line and ground is sufficient to alter switching transients to safe values. The capacitor slopes the wave fronts, producing a more uniform voltage distribution through the machine winding with the result that the voltage differential between turns is reduced.

Applying surge protection

In the case illustrated in Figure 8, a transformer is connected to an exposed overhead incoming line. On the secondary of the transformer are several machines connected to a common bus. Lightning arresters protect the transformer windings from incoming surges and reduce the magnitude of surges transmitted through it. Capacitors and lightning arresters, if used on the transformer secondary, are for surge protection of the four motors connected to the common bus.

In applying this protective equipment, we have a choice of three schemes:

1. We may place a set of 0.5 microfarad capacitors and a set of lightning arresters, if required, at the terminals of each machine. This scheme, while the most reliable, can become quite expensive when several machines are involved.
2. We may place a set of 0.5 microfarad capacitors and a set of low voltage arresters at the common bus of all the machines. This scheme gives adequate protection against all surges coming in over the line, and also against any overvoltage in the secondary circuit developed by reflections. This scheme does not, however, protect against switching transients originating at the breakers.
3. Our third scheme is a modificaton of the second one and consists of adding smaller capacitors of the order of 0.1 microfarad between the breaker and the terminals of the machine to protect against steep switching transients. In this scheme, we also install the arresters and 0.5 microfarad capacitors on the common bus as in scheme two.

When choosing between these three methods, consideration should be given to the importance of the machines, the number of machines, the service the machines are subjected to, and the cost for each method of protection.

Pf correctors are not surge protectors

Figure 1 shows an installation in which fused power factor correction capacitors are installed between the circuit

	STANDARD STATION TYPE ARRESTERS			SPECIAL ARRESTERS FOR ROTATING MACHINES		
SYSTEM VOLTAGE KV — RMS	ARRESTER RATING KV — RMS	IMPULSE SPARKOVER KV — CREST 1½ x 40 WAVE	MAXIMUM DISCHARGE V. AT 1500 A. KV — CREST	ARRESTER RATING KV — RMS	MAXIMUM IMPULSE SPARKOVER KV — CREST*	MAXIMUM DISCHARGE V. AT 1500 A. KV — CREST
2.4 Ungrounded	3	10	9	3	9.5	9
4.16 Grounded	3	10	9	3	9.5	9
4.16 Ungrounded	6	19	18	4.5	14.5	13
4.8 Grounded	6	19	18	4.5	14.5	13
4.8 Ungrounded	6	19	18	6	19	18
6.9 Grounded	6	19	18	6	19	18
6.9 Ungrounded	9	27	27	7.5	24	21
11.5 Grounded	9	27	27	9	28	27
11.5 Ungrounded	12	39	36	12	37	36
13.8 Grounded	12	39	36	12	37	36
13.8 Ungrounded	15	49	45	15	46	45

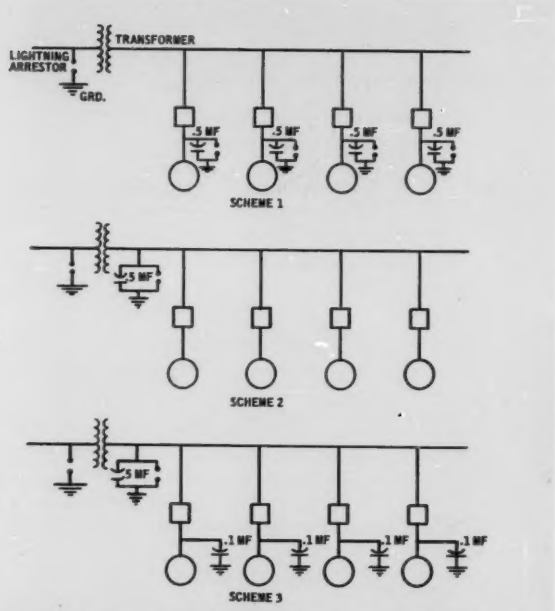
* Wave front of 10 Microseconds to breakdown.

SPECIAL ARRESTERS for rotating machines have different characteristics than standard station types. **(FIGURE 7)**

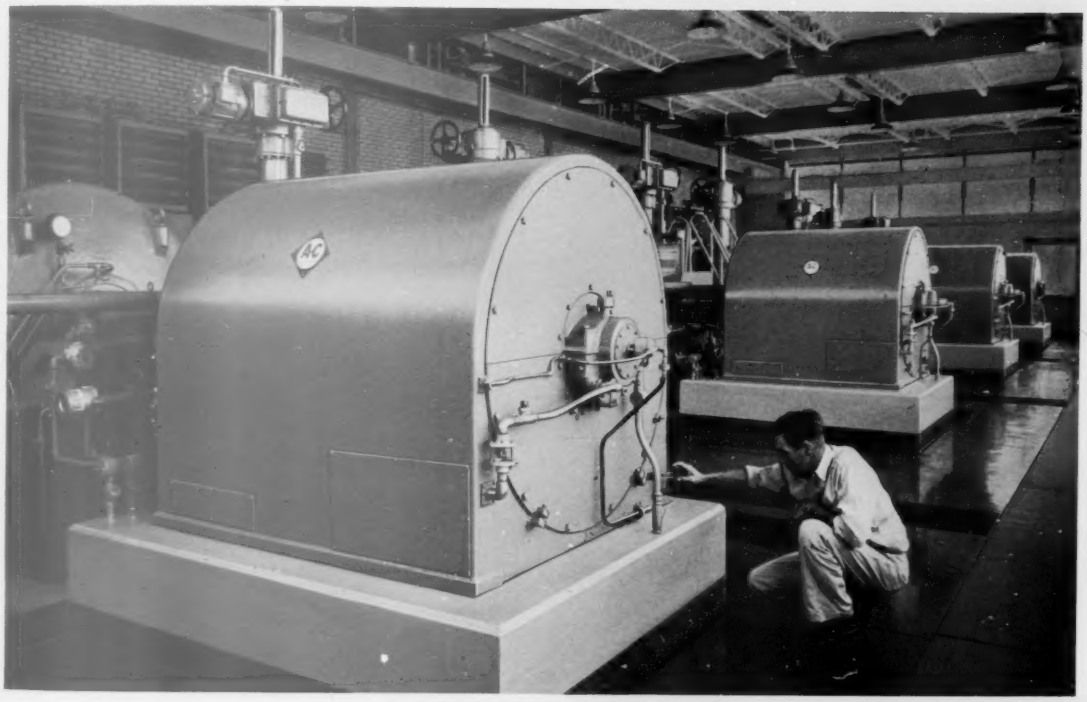
breaker and motors. This is quite a common practice, and the question has often arisen as to how power factor correction capacitors differ from surge protective capacitors. The power factor correction capacitor generally has a very high microfarad value and should be very effective against surges. However, a power factor correction capacitor is not considered a surge protection device because it is fused. The fuses are most likely to blow during a lightning storm when surge protection is needed most.

Power factor correction capacitors, when applied between the circuit breaker and the motor as shown in Figure 1, offer effective protection against switching transients. Switching transients are very low in magnitude and do not blow the capacitor fuses.

Remember, however, that fused power factor correction capacitors can be used only for protection against switching transients. Lightning arresters and surge protection capacitors are necessary to protect rotating machine insulation from surges transmitted through the transformer. Referring to scheme No. 3 of Figure 7, the power factor correction capacitors can only replace the 0.1 mf capacitors. The lightning arresters and 0.5 mf capacitors are necessary.



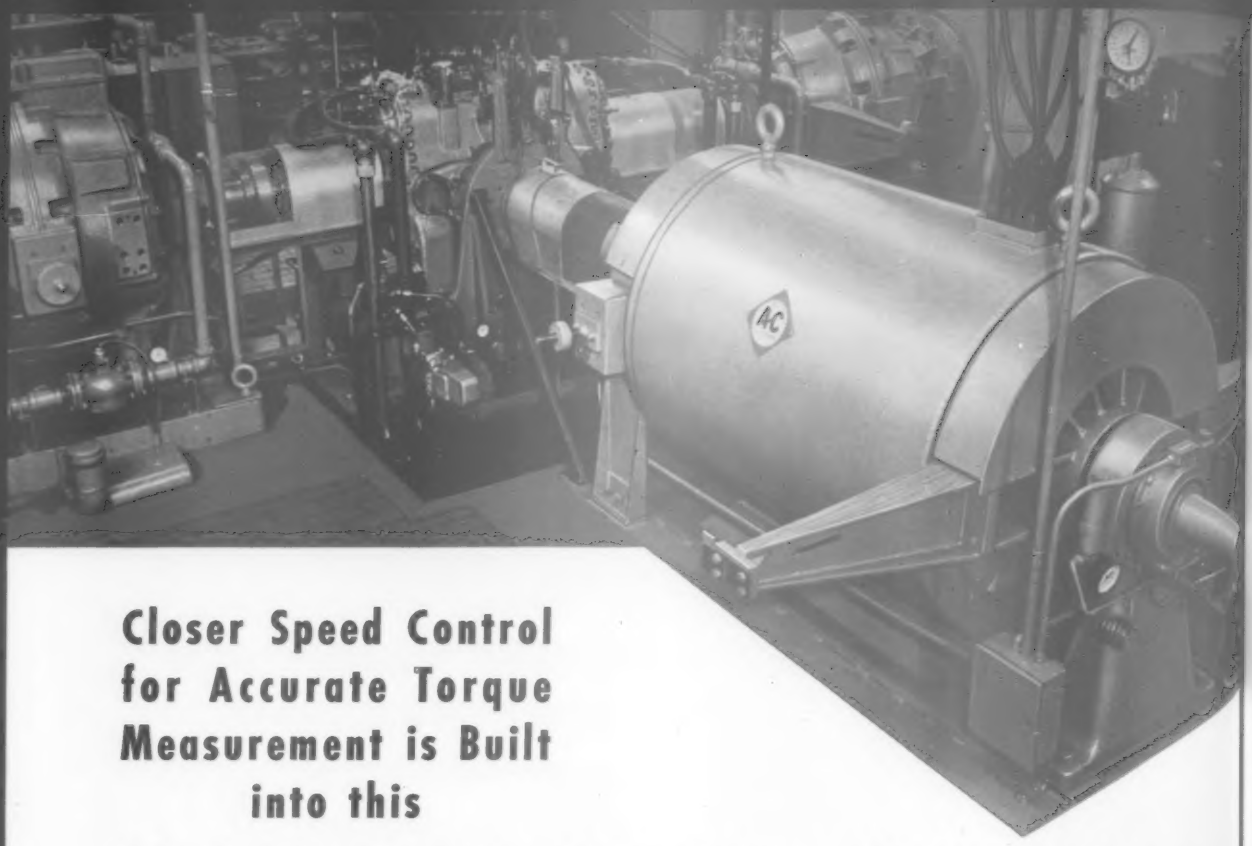
HERE ARE THREE WAYS of applying surge protection. **(FIGURE 8)**



TYPICAL OF MOTORS protected by unit substations are these 2500-hp, 4160-volt, 3600-rpm motors on a natural gas pipe line.

SMOOTH SHAVE for the top flange of this huge condenser shell gives an even face for a vacuum-tight joint. When attached to the exhaust nozzle of a 120,000-kw cross-compound reheat turbine, its nearly 15,000 tubes will carry cool Lake Michigan water through 85,000 square feet of condensing surface for unusually high vacuum operation at the power plant shown on the cover.

A-C Staff Photo by J. Gosseck



Closer Speed Control for Accurate Torque Measurement is Built into this

VARIABLE FREQUENCY DYNAMOMETER

by **E. H. FREDRICK**
Chief Application Engineer
Dynamatic Corp.
and
M. F. GAY
Motor and Generator Section
Allis-Chalmers Mfg. Co.

Hydrostatic bearings, water and forced air cooling, plus a motor that operates as a rotating transformer, are unique features of this testing equipment.

IN JANUARY of 1952 a new type dynamometer was put into service in the laboratory of one of America's foremost automotive manufacturers. It is being used to test torque converter type transmissions used in heavy military tanks.

Selecting the type of drive and designing the dynamometer posed many problems. It had to be sensitive, develop up to 900 hp at 3180 rpm, and maintain constant torque capacity down to 350 rpm. Major considerations in selecting the type of drive were reliability, simplicity, performance, first cost, maintenance costs, and flexibility in operation. After a careful study of the factors involved, a variable frequency drive appeared to have many advantages.

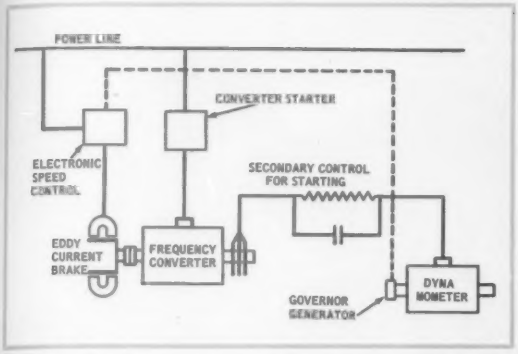
The load curve described was ideally suited to the use of a variable frequency induction motor. Therefore, a relatively standard 1000-hp, 3580-rpm, 60-cycle cage motor was selected as the dynamometer motor. The required 3180 rpm was to be obtained at 54 cycles. The speed range was to be covered by a frequency range of 54 to 10 cycles, which is a very conservative range of operation for a well-designed variable frequency system.

Induction frequency converter selected

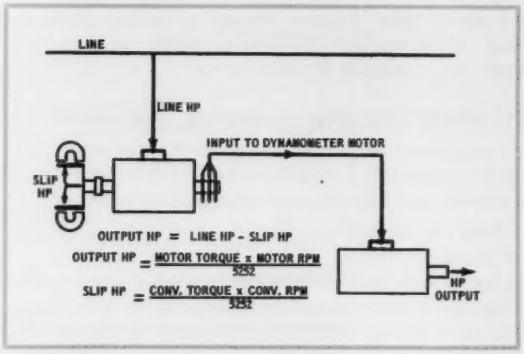
Because operation at or very close to 60 cycles was not required, the use of a 1250-hp, 4-pole induction frequency converter was selected as the most economical source of variable frequency. In the required range of operation, converter speed is always less than synchronous speed, while the torque developed and the direction of rotation are always the same. Therefore, the frequency can be controlled readily by an eddy current inductor brake regulating the speed of the frequency converter. The simple block schematic diagram (Figure 1) shows the units involved in this application, and Figure 2 shows the power flow and distribution in the various units.

Functional operation of the drive

The functions of the various units in the system are illustrated by a description of the starting of the drive and bringing it to a set speed. The induction frequency con-



MAJOR COMPONENTS are shown in this block diagram. **(FIGURE 1)**


LINE
LINE HP
INPUT TO DYNAMOMETER MOTOR
SLIP HP
OUTPUT HP = LINE HP - SLIP HP
OUTPUT HP = MOTOR TORQUE x MOTOR RPM / 5252
SLIP HP = CONV. TORQUE x CONV. RPM / 5252
HP OUTPUT

POWER FLOW while motoring is in the direction indicated. **(FIG. 2)**

verter is, for all practical purposes, a wound-rotor induction motor. In starting the induction frequency converter, a resistor in series with the dynamometer motor is first connected across the slip rings. Then the line switch to the stator is closed just as with any wound-rotor motor. The converter then accelerates to very near synchronous speed, and the rotor of the de-energized eddy current brake is accelerated with it. At this speed the voltage and frequency across the slip rings of the induction frequency converter are very nearly equal to zero. The squirrel-cage motor terminals may now be connected directly to the slip rings by bypassing the resistor. Since the voltage and frequency are not sufficient to turn over the dynamometer motor, a static condition on the motor results.

If at this time the eddy current brake is energized, it will develop a braking torque which will decrease the speed of the wound-rotor induction frequency converter. As speed decreases, the frequency and the voltage across the slip rings will increase. At a low frequency there will be sufficient voltage across the rings of the converter and the dynamometer stator to start the dynamometer motor. After it is started, speed of the dynamometer motor can be easily and accurately controlled by adjusting the excitation of the eddy current brake. This will control the speed and output frequency of the converter and conversely the speed of the dynamometer motor.

In practice it is not feasible to adjust the brake excitation manually. To maintain constant speed, a change in torque demand on the dynamometer motor must be matched almost instantly by an adjustment in brake excitation. To accomplish this, a governor-generator driven by the dynamometer motor provides a control signal to an electronic control. The electronic control automatically adjusts brake excitation in response to the governor-generator signal. By this means, speed is controlled very accurately and with fast response.

Drive supplies needed torque and speed

Data obtained from a combined test proved that the drive and its components more than met all the requirements. Full-load torque was available above and below as well as throughout the specified speed range. At full rated torque, the minimum rated operating speed of 350 rpm was obtained at a frequency of approximately 6 cycles per second, and full rated torque was developed at a frequency several cycles less than this. On test, the drive operated successfully on reduced torque at frequencies as low as 2 cycles per second. Although top rated speed was 3180 rpm, full rated torque was still available at 3220 rpm, achieved at a frequency of 54 cycles per second.

Speed control accuracy and ease of adjustment also met the requirements set up for the drive. These tests demonstrated that the designs of the dynamometer drive motor and induction frequency converter were such that, at all operating frequencies, stability of the alternating-current loop, breakdown torque of the dynamometer drive motor, and slip of the dynamometer drive motor were better than required to make this a successful drive.

Dynamometer friction reduced

One of the prime requirements of this application is the accurate measurement of motoring torque. Extreme care was taken to minimize losses which would impair sensitivity or accuracy. The dynamometer motor shown in Figure 3 is cradled in hydrostatic lift trunnion bearings. These bearings support the entire motor unit on two trunnions built integrally with the motor end housings. High pressure oil jacking allows the motor to float on a film of oil and practically eliminates any frictional resistance to the rotation of the stator within the very limited arc of travel necessary to actuate the torque measuring equipment. The torque reaction between the motor rotor and stator is transferred from the stator through a torque arm mounted on the side of the stator to a pneumatic balancing device. The balancing device measures in air pressure the pounds of force necessary at the end of the torque arm to balance the torque reaction in the stator.

To minimize parasitic frictional drag, all connections to the motor are on the vertical centerline. The motor leads are brought out from the top of the motor, are extra long, and are made from very flexible cable. The ventilating air is carried through the base of the motor by means of a duct, with a narrow circumferential clearance between the duct and the stator to prevent any drag from that source. Forced ventilation by means of a suction blower is necessary because the constant torque output requirement results in full motor losses at low speeds. Oil lines to the rotor bearings have flexible connections, and the

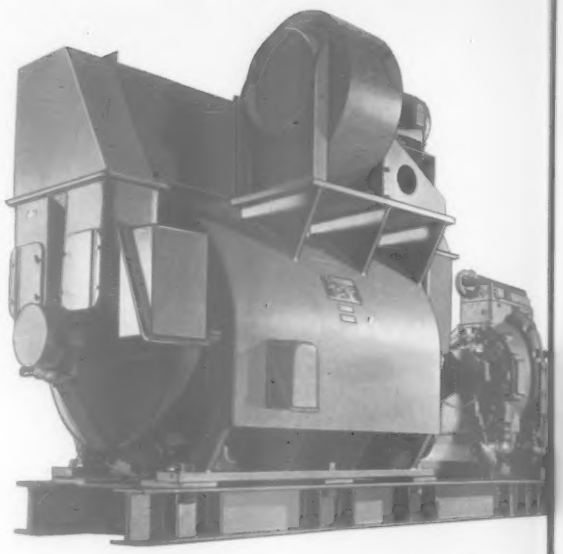
oil outlets have telescope fittings to further minimize drag. Care was also exercised to design the rotor and stator for minimum windage torque.

Frequency converter a rotating transformer

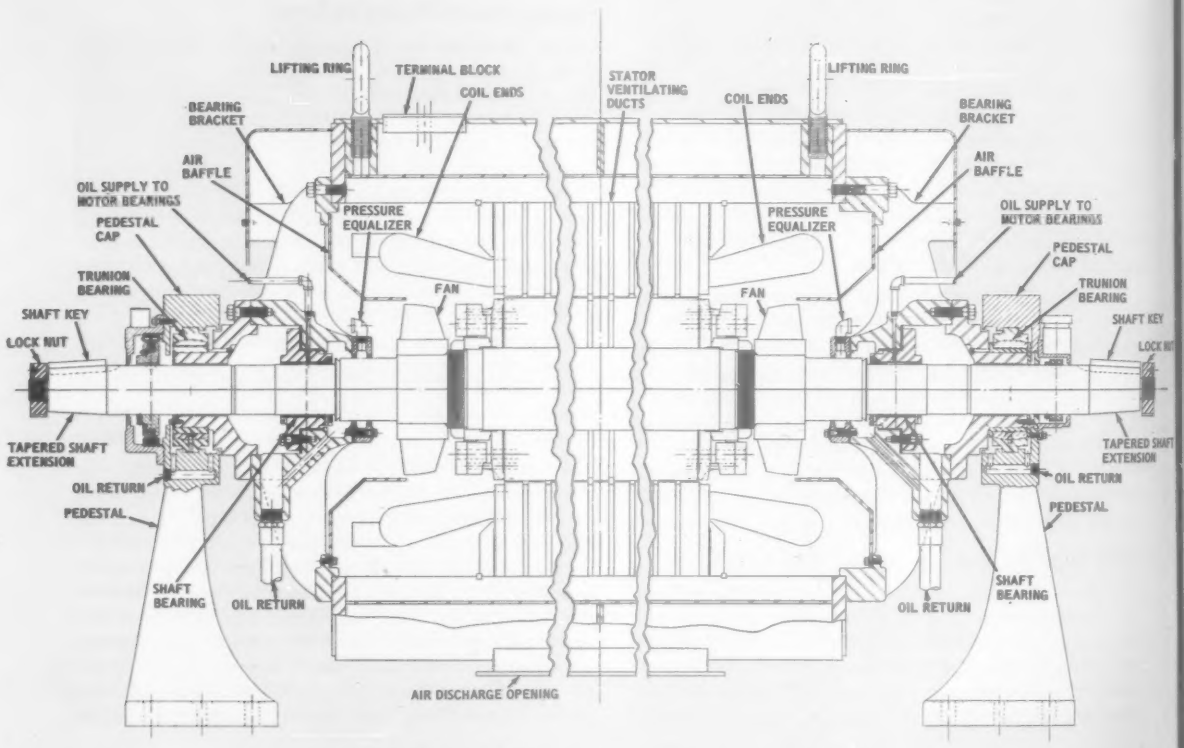
As mentioned previously, the induction frequency converter is essentially a wound-rotor motor with special characteristics and operates as a rotating transformer.

Since the rotor frequency varies directly in proportion to slip speed (which is the difference between the synchronous speed and rotor speed), control of rotor output frequency is accomplished by controlling the rotor speed. The open circuit rotor voltage produced is also directly proportional to the frequency. Because of this, when the dynamometer motor is connected to the rotor, a constant ratio of voltage per cycle is obtained if regulation caused by load changes is neglected. This inherent feature of the induction frequency converter is ideal for the service required, since in operation on variable frequency constant volts per cycle are required by the dynamometer motor on a constant torque load curve.

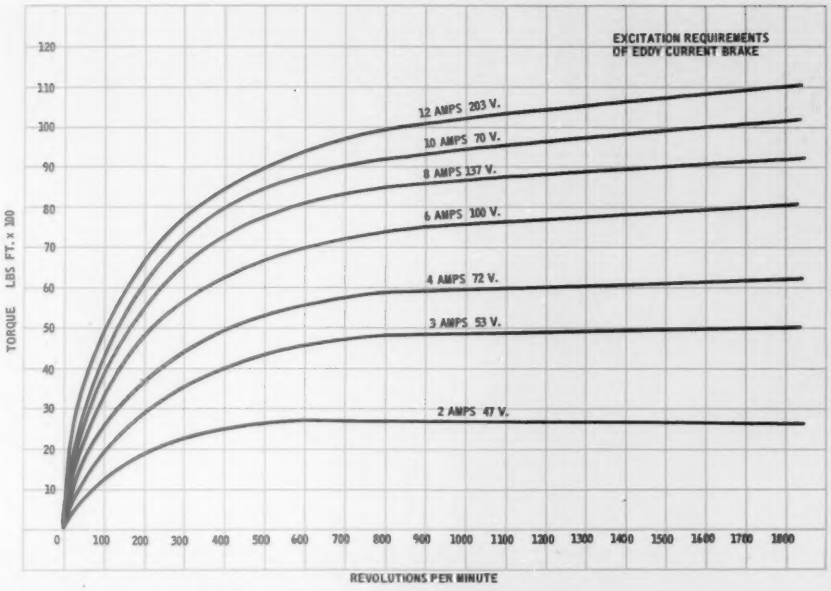
Forced ventilation is required at the lower speeds of operation because the converter operates with constant torque capacity over a speed range of 180 to 1620 rpm. The ventilating air is taken from the room by a top



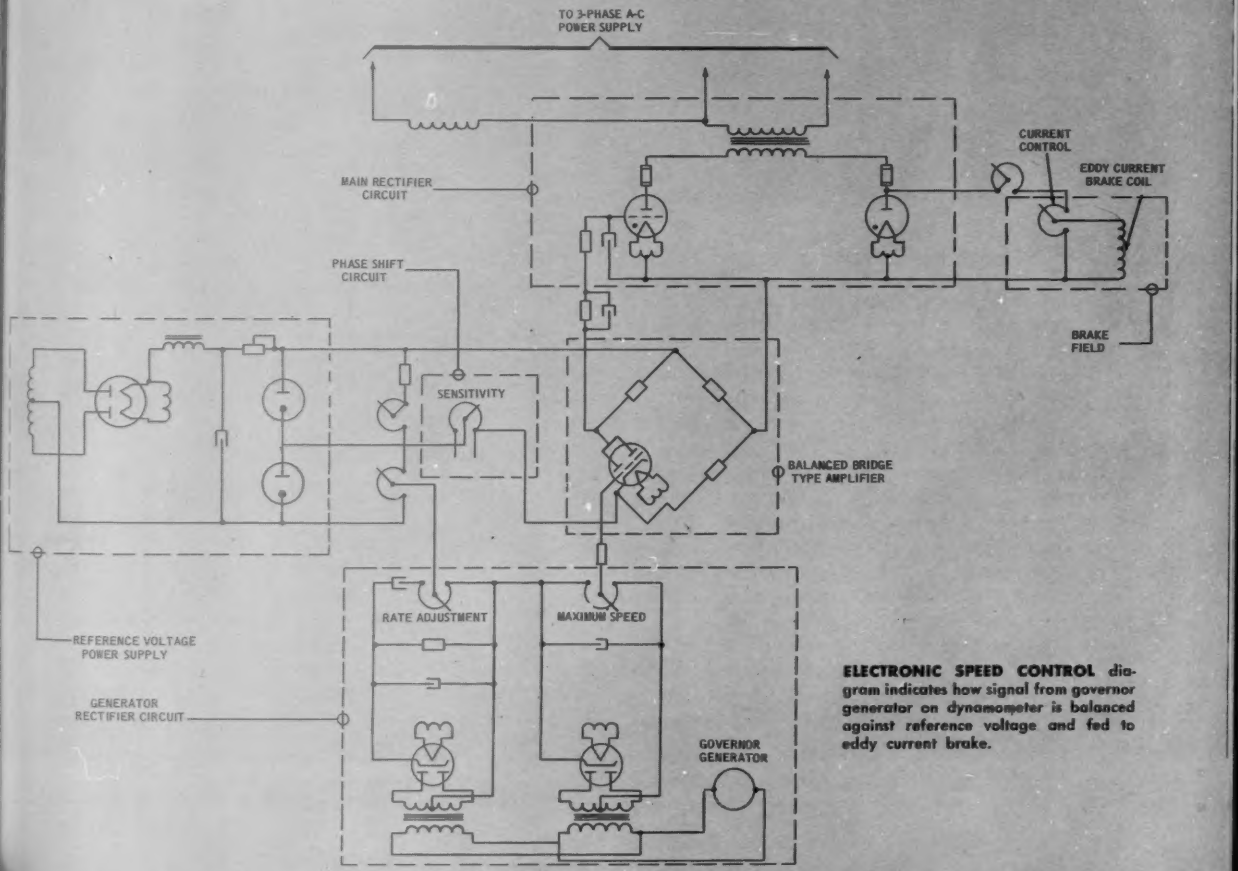
FREQUENCY CONVERTER has a frame mounted blower to force circulation of cooling air. **(FIGURE 4)**



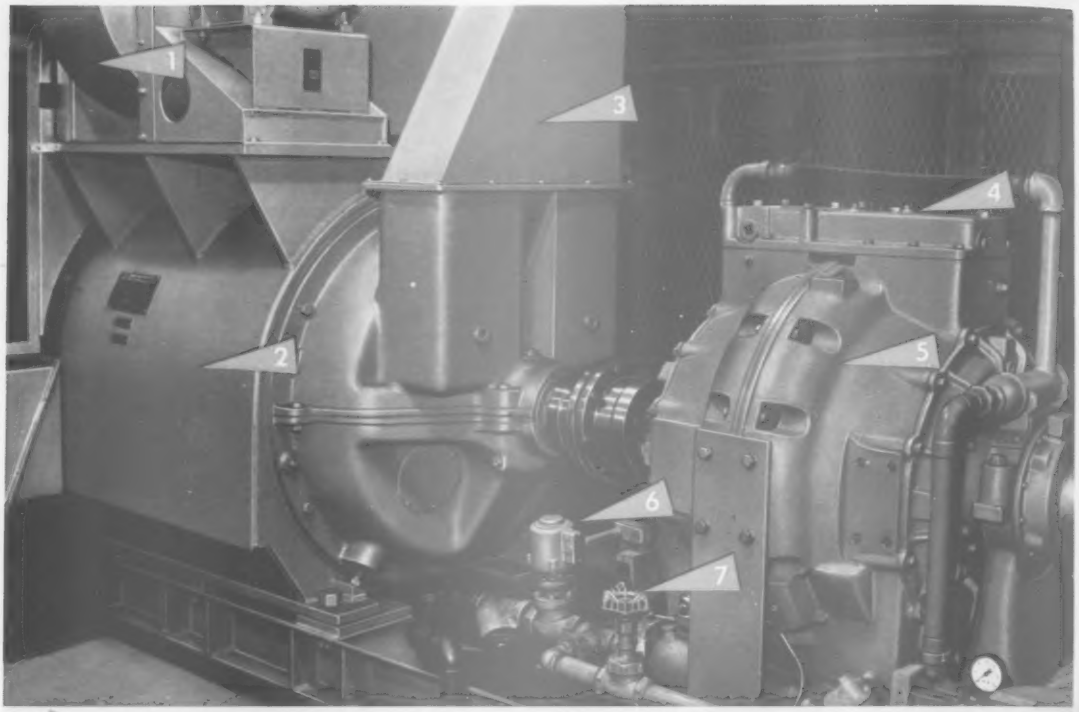
CONSTRUCTION DETAILS of the dynamometer are shown in this cross-section drawing. High pressure oil is pumped to trunnion bearings to float entire motor on a film of oil. **(FIGURE 3)**



VARYING REQUIREMENTS for eddy current brake excitation are indicated by these curves. **(FIGURE 5)**



ELECTRONIC SPEED CONTROL diagram indicates how signal from governor generator on dynamometer is balanced against reference voltage and fed to eddy current brake.



1 Blower for Forced Ventilation
2 Frequency Converter
3 Ventilating Ducts
4 Water Chest
5 Eddy Current Brake
6 Automatic Water Control Valve
7 Manual Water Valve controlling flow to eddy current brake

ABSORBING UP TO 1000 hp requires water cooling of eddy current brake. Converter is forced air cooled.

mounted, motor driven blower which forces it through the converter and discharges it from the converter back into the room. Figure 4 shows a view of the converter-brake set.

Eddy current brake controls speed

The heart of the speed control scheme is a simple inductor type eddy current brake. It is water cooled because under certain conditions it may be called upon to absorb as much as 1000 hp. To carry away the heat generated by that amount of power requires a flow of nearly 75 gallons of 90 F cooling water per minute.

The brake consists of a stator which acts as the magnet frame and incorporates a single toroidal coil for excitation. The rotor is toothed, similar to a spur gear. As the rotor turns in the stator, the rotor teeth set up a pulsating flux in the cylindrical stator pole faces. The flux pulsations generate eddy currents which react with the magnetized rotor teeth to develop torque. The amount of torque developed is dependent on both excitation and speed and varies as shown in Figure 5.

Cooling water is injected into the air gap of the brake, over the surfaces in which the eddy currents are developed. Consequently, the area in which the brake heat is generated is scoured with coolant, and very effective absorption of the brake heat is realized. Automatic temperature controls regulate the flow of cooling water in accordance with the demand on the brake.

Speed control

The brake magnets are energized by a single coil which requires only 2 kw for maximum excitation. Since the excitation power is very low it is easily supplied by a small electronic speed regulating control. In service, the speed control held the speed within ¼ of 1% of top speed over a range from 2 to 57 cycles, which exceeded requirements by a considerable margin. Speed is set by adjusting a small potentiometer in the grid circuit of the control, thus controlling a 1000-hp motor with a few watts. A simplified schematic diagram of the control is shown.

Modification of components broadens usage

The successful application of this dynamometer opens up an entirely new field, not only for large, high speed dynamometers, but also for solidly mounted adjustable speed drives. The use of a simple squirrel-cage motor results in a compact drive unit, minimizing floor space requirements at the driven machine where space usually is an important consideration. The squirrel-cage motor lends itself to high speed operation as no other electrical motor does. Within mechanical limits, it can be utilized direct-connected in many applications formerly requiring gears. Furthermore, the squirrel-cage motor is relatively rugged, simple in its construction, and will require only minimum maintenance. The speed control is also simple and adjustments are easily made by changing the setting of small resistors.

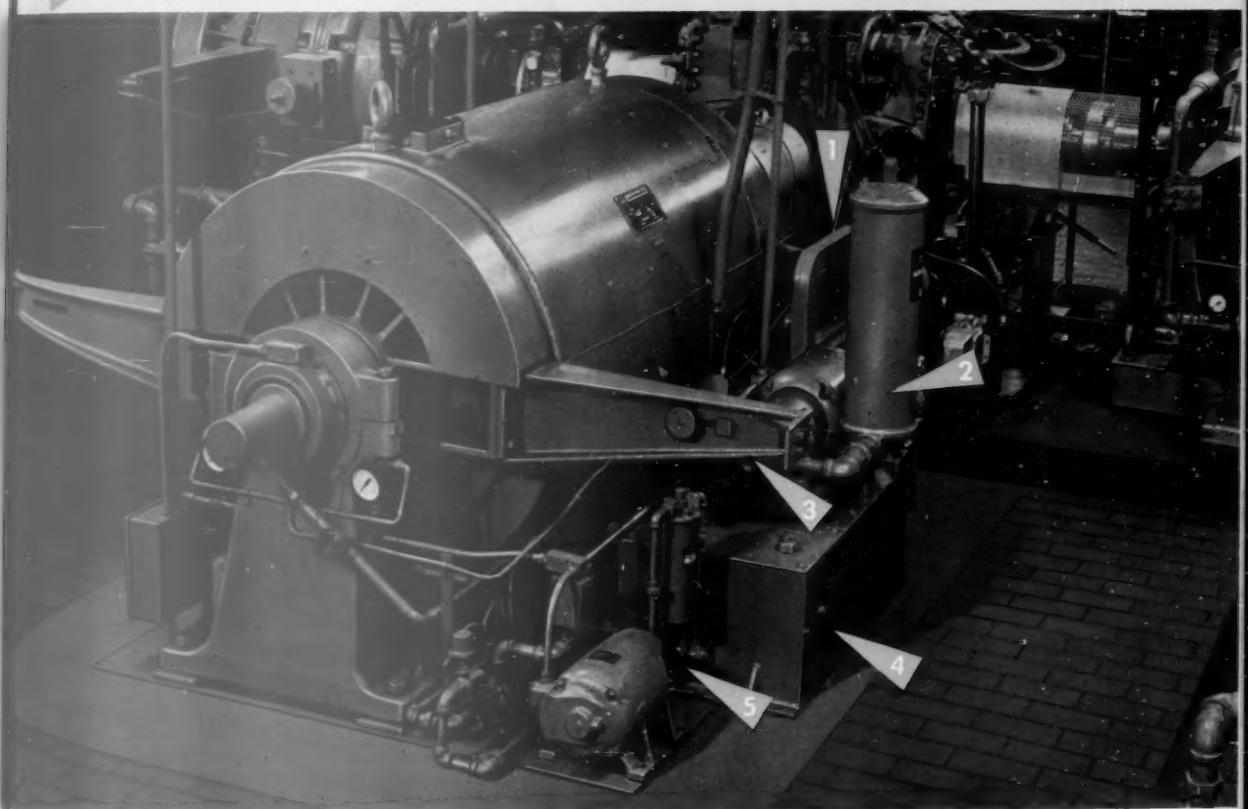
Modifications of the basic machinery arrangement used in this drive are made to meet the special requirements of other applications.

For example, when it is necessary to operate at frequencies above 60 cycles per second, the eddy current brake can be replaced by an eddy current coupling. When driven by either an induction or synchronous motor, an arrangement such as this can be economical to frequencies of 90 cycles per second or more if the load speed torque curve permits. If operation both above and below 60 cycles per second is required, a two-speed motor is used to drive the eddy current coupling.

Speed ranges and speed torque curves that the induction frequency converter cannot economically take care of are often accommodated by another modification. The induction frequency converter is replaced by a synchronous generator which is driven through an eddy current magnetic coupling by either an induction or synchronous motor.

With higher speed testing such as required for aircraft components becoming a greater problem daily, the variable frequency drive which is adaptable to dynamometer operation promises to become more prominent and will probably find much wider use in the very near future.

1. Torque Measuring Arm
2. Low Pressure Lubricating System
3. Torque Calibrated Arm
4. Oil Sump Tank
5. High Pressure Lubricating System for hydrostatic trunnion bearings



TWO LUBRICATING SYSTEMS are used to assure minimum friction, accurate torque measurement. The low pressure system supplies normal lubrication, high pressure system floats entire dynamometer motor.

Selecting Control

FOR HEAVY MACHINERY

SERIOUS LOAD PROBLEMS result when run-of-the-mine iron ore is fed to a primary crusher like this 54-inch unit.

by **W. R. PATTERSON**
Crushing, Cement, and Mining Sections
and R. A. GERG
Control Section
Allis-Chalmers Mfg. Co.

Coordination is the key to trouble-free operation of today's heavy machines.

TODAY'S LARGE MACHINES frequently cause voltage problems which not only affect their own motors and control but also create problems for other equipment operating on the same feeder. Motors and control operating on heavy machines, such as large rock and ore crushers, must be designed especially for their application.

After blasting has removed the ore or stone from the earth, the crushing operation in many mining and stone-crushing plants is divided into several stages, which are usually referred to as the primary, secondary, tertiary, etc. The crushers used may be of either the jaw or gyratory type. A comparison of various types is shown in Table I. However, since primary gyratory crusher loads fluctuate more severely than other types, they illustrate the problem best.

The selection of the primary crusher is based on the feed opening required and the tonnage. For example, in a 400-ton-per-hour plant, the primary crusher might be a unit weighing close to a quarter million pounds. Out of this weight, the mainshaft assembly, which includes the shaft and crushing head, together with the eccentric and other rotating parts, weighs in the neighborhood of 50,000 to 60,000 pounds. Setting these parts in motion requires a high starting torque to overcome a considerable amount of inertia and friction.

Specially designed motors are available for crusher operations. They have a high starting torque and adequate running torque to handle the maximum anticipated peak loads.

In the majority of applications a wound-rotor motor is used for driving primary gyratory crushers. The wound-rotor motor permits controlled acceleration of the crusher and limits the starting current to a value that minimizes the voltage dip. It also provides adequate starting torque to accelerate the crusher smoothly.

The rotor leads are connected to a resistance bank, and acceleration of the motor is accomplished by progressively shunting out this resistance until the rotor terminals are shorted. The shunting of the secondary resistor bank may be done automatically or by means of a hand-operated drum switch.

Stone is dumped into the primary crusher in loads varying from five to twenty tons. The finer stone, which drops into the bottom of the crushing chamber, requires from 60 to 90 percent of the motor horsepower output. In addition, there may be in the crushing chamber a number of pieces ranging in size from 30 to 40 inches in diameter. When the head first begins to nip or crush these pieces and at the same time crush the finer stone, peak momentary loads of 150 to 200 percent of the motor horsepower may be experienced, even though the average horsepower requirement for crushing the entire load of stone may be 50 to 75 percent of the motor rating. When

TYPE CRUSHER	LOAD FLUCTUATIONS	DUST	NORMALLY OVERLOADS AT TIMES	AVERAGE % PEAK LOAD	DC OPERATING MAGNET RECOMMENDED ON CONTROLS	INSTANTANEOUS OVERLOAD RELAY REQUIRED
PRIMARY GYRATORY	Severe	Yes	Yes	150-200	Yes	Yes
SECONDARY GYRATORY (no fines)	Moderately Severe	Yes	Yes	100-150	Yes	Yes
TERTIARY GYRATORY	Steadier	Yes	No	100-115	Yes	No
JAW PRIMARY	Similar to Gyratory Secondary (due to flywheel)	Yes	Yes	100-200	Yes	Yes

TABLE I

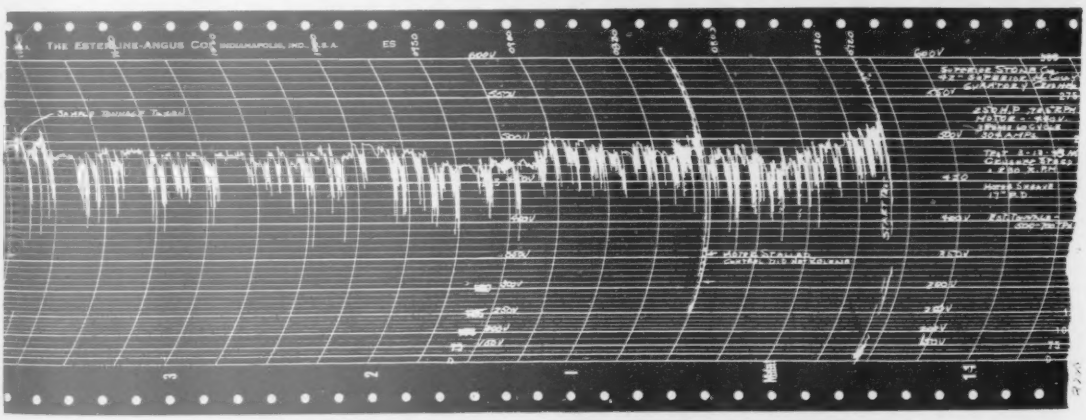
running idle or lightly loaded, which is normal between loads, the crusher may only draw 20 to 30 percent of the motor rating. These wide load fluctuations make it difficult to provide adequate overload protection.

Low voltage can be costly

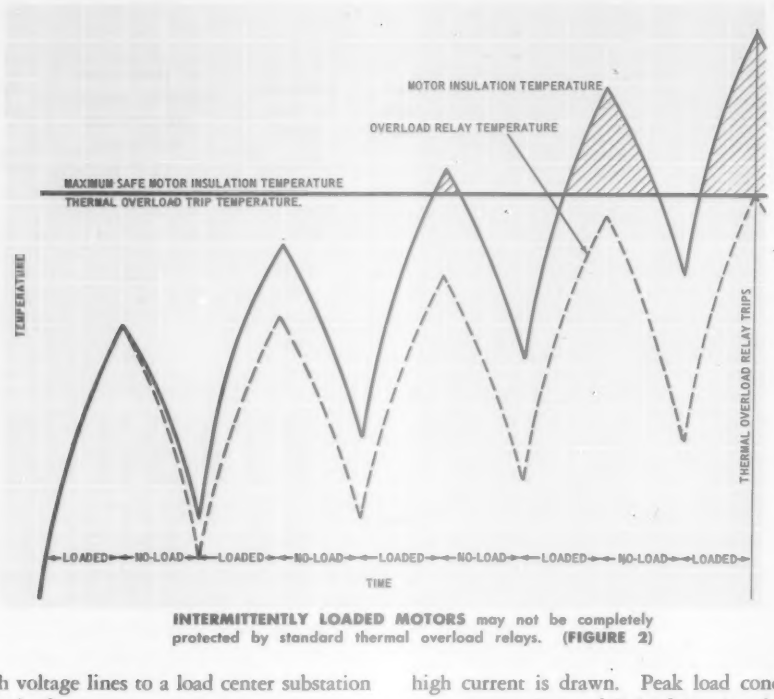
A widely fluctuating load, such as shown by the recording voltmeter chart in Figure 1, often results in poor voltage regulation. As the torque required of the driving motor increases, the power drawn from the distribution system increases and, generally speaking, results in lower voltage being applied to the motor and starter terminals. A dip in supply voltage to the motor results in reduced motor driving torque, which means an increased demand for amperes from the line. This, in turn, further reduces the supply voltage. Low voltage may have several serious results. The motor may stall or the motor starter contacts may freeze, and the net result may be a prolonged shutdown and consequent loss in production. If stalling occurs just after a 20-ton load has been dumped into a primary crusher, up to eight hours may be required to remove the stone either by hand or by small hoist. This loss of production in some plants may cost upwards of $5,000 a day.

Since low voltage is one of the most serious problems encountered by the operators of a crusher plant, a study of the coordinated design of the utility distribution system and the distribution layout within the crusher plant should be the first step in the elimination of low voltage problems. However, caution must be observed so that low voltage conditions will not prevail in spite of this coordinated planning. One of the most common oversights is to plan the distribution system on the basis of rated horsepower loading. In many plants the primary gyratory crusher alone will equal 20-50 percent of the total loading. On a distribution system designed for rated load, a serious voltage dip may occur when a load is dumped into the primary crusher and its driving motor suddenly draws up to 200 percent of rated current.

Frequently, long low voltage lines are run to heavy loads that are in remote parts of a plant. Since low voltage lines are a major source of voltage troubles, power losses can be minimized by shortening these lines and



VOLTAGE FLUCTUATIONS with severe load changes are shown by the recording voltmeter chart taken under normal load conditions at a primary crusher. **(FIG. 1)**



INTERMITTENTLY LOADED MOTORS may not be completely protected by standard thermal overload relays. **(FIGURE 2)**

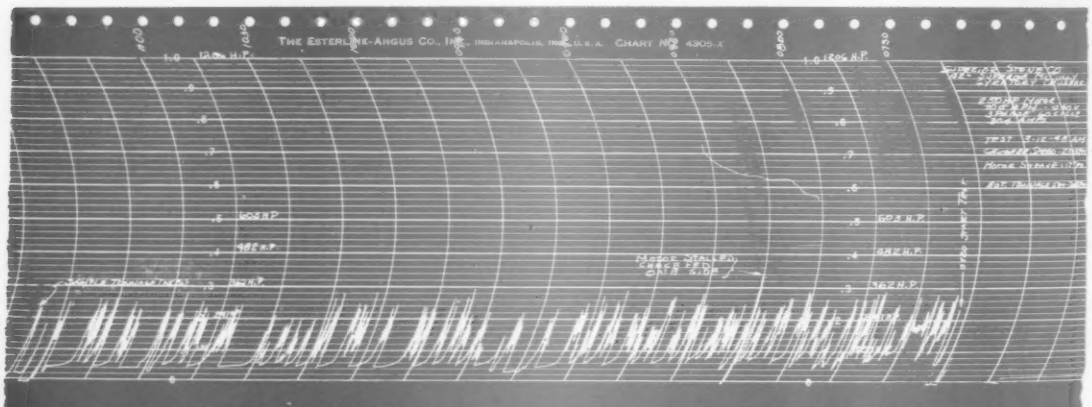
bringing the high voltage lines to a load center substation installed near the load.

The majority of troubles occur on installations already located on long utility distribution systems where no corrective action can be taken. In these cases the motor control must be designed to operate properly under the existing voltage conditions.

Standard motor starters are equipped with an operating magnet. In general, these magnets are designed to pick up at 80 to 85 percent rated voltage and drop out at some value less than the pickup value.

During a peak load the voltage may dip well below 85 percent rated value and cause the starter to drop out even though the peak may be momentary. These dips in voltage impose additional burden on the contacts. Contact pressure may be momentarily lowered at the instant high current is drawn. Peak load conditions almost always occur when a full load has just been dumped into the primary crusher. If the motor stalls under these conditions, it means that the crusher's full load must be emptied before production can be resumed. Standard ac motor starters can be modified for these applications.

Direct-current magnets energized from the ac line through a dry-type rectifier as a separate source of dc will keep the drive motor starter contacts closed to a much lower value of voltage than will an ac magnet. When direct current is available it may be used instead of rectified ac. A dc unit designed for the application will, if desired, keep power connected to the crusher drive motor at substantially lower dips than an ac magnet. It is important to note here that when the voltage dips at the terminals of the primary crusher control, the same voltage



LOAD CONDITIONS determine need for additional protection. Chart in Figure 1 corresponds with load chart shown. **(FIGURE 3)**

dip is present at the terminals of all other motor controls. Therefore, unless these controls are also equipped with dc magnets they will drop out and disconnect their motors from the line.

Dust is a troublemaker

Dust, an enemy of all electrical equipment, is common to all crusher installations. An accumulation of dust on the coils of the motor thick enough to increase the temperature of these windings 10 degrees C would also reduce the life expectancy of the winding by approximately 50 percent. Dust in the bearings or guides of the control equipment or on its contacts may cause faulty operation or complete failure.

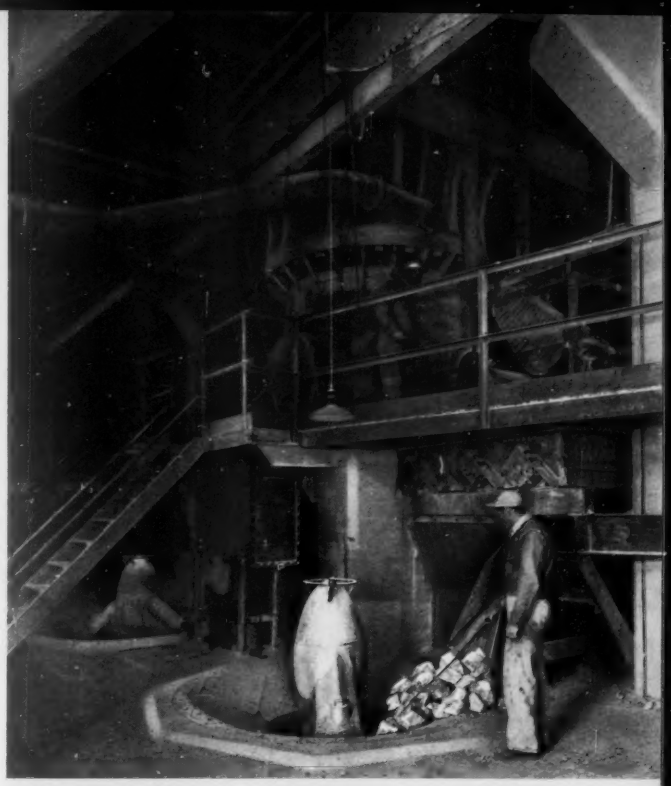
There are three general types of control enclosures available for use around crushing operations. They are: NEMA 1A — Semi-dust-tight, NEMA 4 — Water-tight, and NEMA 5 — Dust-tight.

NEMA 1A is a NEMA 1 enclosure with gaskets and affords some protection. NEMA 4 and NEMA 5 enclosures are very similar in construction, with the major difference being the gaskets used to seal the enclosure. As a rule, NEMA 4 uses a rubber gasket and NEMA 5 uses a felt gasket. Experience has shown that the felt gasket may take a permanent set in a relatively short time. Rubber gaskets, however, have proved themselves capable of providing an effective seal over a long period of time. NEMA 4 is therefore recommended where rock dust or similar materials are handled. Caution should be observed on the part of the operators so that the enclosure cover is not inadvertently left open and thus defeat the purpose of the rubber gasket.

It is important that the main contact surfaces of starters be in a vertical plane. Contact surfaces in a horizontal plane and not shielded from dust will collect dust at an accelerated rate and then may fail to perform their designated function.

It may appear that no overload protection is necessary because during 90 percent of the crushing period the crusher motor is operating at 50 to 75 percent rated hp. Normally the winding temperatures are well below safe limits and the momentary peak loads will not raise the temperature beyond safe limits. However, any protective device used is always placed where it is to handle the unusual conditions rather than the average. In a crusher plant a heavy load, a piece of tramp iron, faulty bearings, or any one of many other things may bring on the unusual condition that could result in burned out motor windings if no overload protection is provided. For this reason, all crusher motors must have adequate overload protection. The cost of adequate protection is very small when compared to cost in terms of lost production or of rewinding the motor.

It has been standard control practice to furnish two or three thermal relays in the starter enclosure. These relays have been designed to somewhat approximate the heating cycle of a motor winding. Normally, this process will remove the motor from the line when the motor insulation reaches a dangerously high level. However, in a crusher application such a standard relay mounted remote from the motor offers little or no overload protection because



PRIMARY CRUSHER OUTPUT is screened prior to secondary crushing. This process reduces secondary load fluctuations.

of the widely varying load conditions. Even though the thermal relay can very successfully follow the heating cycle of a motor when both start out at the same temperature, it cannot follow the cooling cycle of the motor. Since the relay weighs only a few ounces, while the motor may weigh several thousand pounds, the relay, of course, will cool much faster than the motor. Figure 2 illustrates the relative heating and cooling cycles and shows the possibility of eventual burnout of the motor insulation.

Protection based on winding temperature

If proper overload protection is to be obtained for a primary gyratory crusher motor, standard overload protectors must be replaced with or supplemented by special overload devices. One such unit is the bimetallic thermal sensitive overload device located on or near the actual motor windings to be protected. An embedded temperature sensitive conductor used with a relay may also be employed. Actual temperatures of the motor windings can then be measured, whether on the heating or the cooling cycle. The actual location of the bimetallic element may vary; however, the effectiveness of the unit is not materially altered by any of these standard locations. The bimetallic element is located on the iron adjacent to the coils on some designs of motors up to 200 hp. On larger motors it is located on the actual motor windings.

Thus, full overload protection, with the resultant elimination of expensive motor burnouts and production losses, can be obtained by means of a small additional expenditure.

This overload device can be used in a variety of ways, depending upon the wishes of the plant operator: It can

be used to shut down the crusher motor the instant a dangerous temperature is reached; it can be used to sound an alarm which would permit the operator to complete the crushing cycle before shutting down the motor; or it can be connected to an alarm and timing motor which would give the operator a fixed period of time before the drive motor would automatically shut down.

In any of the above examples, the motor will ultimately be shut down. This means a period of time often exceeding one hour before the crusher motor cools sufficiently to allow the overload to reset its contacts so the motor can be restarted.

An ideal solution to the problem is to have the embedded overload device sound an alarm, warning the operator not to add additional loads. This arrangement would enable the operator to run out the load.

The cooling fans of the motor would then quickly cool the motor to the point where the overload device would reset and shut off the alarm. The operator could then load the machine. This type of protection is used on many marine motors driving vital auxiliaries.

When the crusher is overloaded to the point of stalling, as in Figure 3, it may be desired to disconnect the motor from the line immediately rather than wait for its windings to reach a predetermined temperature level. To do this, an instantaneous overload relay can be furnished and set at a value which permits the drive motor to start without interference but will remove the stalled motor instantaneously from the line.

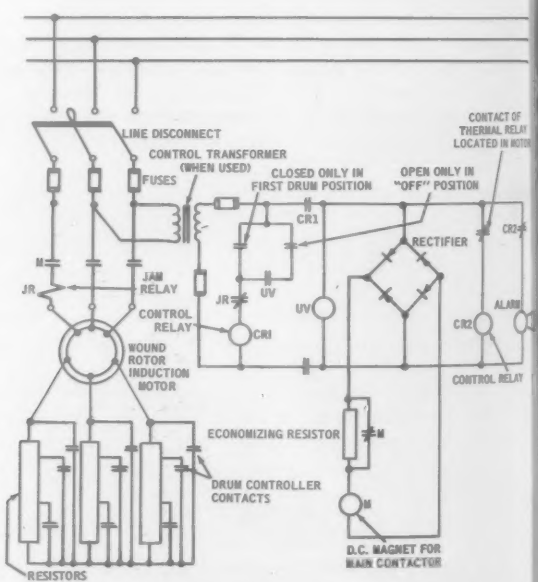
The motor starter and motor should always be provided with short circuit protection in the form of fuses or circuit breakers located between the motor starter and distribution system. Such protection is called for in all national electrical codes and is provided as standard in most localities.

An adjustable time delay drop-out relay is frequently used to restart the crusher motor automatically after a momentary power interruption. If power is not restored within the time delay setting of the relay, the motor must be restarted manually. The relay is usually set so that the starter will not reclose if the motor falls below 50 percent speed. If it is running slower than approximately 50 percent of rated speed, the resultant inrush of current will open the stalled rotor relays or the short circuit protective device. This inrush will be larger than the starting inrush current, because the resistors in the wound-rotor circuit which were in the rotor leads during starting are shunted out once the motor is up to speed.

Coordination between machine motor and control engineering is important in the manufacture of any equipment but is a "must" for heavy machines where severe load fluctuations may stall the motor or damage the machine.

To protect the motor and machine against these load fluctuations, controls generally recommended for machines like heavy crushers or grinders have features beyond those supplied on standard motor controllers. The following devices should be considered when applying new controllers or modernizing old installations with machines having this type of load:

1. Dc magnets to keep starter contacts sealed during abnormal voltage dips.
2. Thermal sensitive relay near the motor windings to guard against burnout.
3. Instantaneous overload relay to remove motor from line on any load which would stall the motor.
4. Time delay undervoltage relay to restart the motor following momentary loss of power.
5. Fuses or circuit breaker for short circuit protection of starter and motor.



COMPLETE PROTECTION can be obtained with only a comparatively small additional investment. **(FIGURE 4)**

JAW CRUSHER LOAD FLUCTUATIONS are partially absorbed by the heavy flywheel mounted on the crusher.

Air Cooled CONTROL TRANSFORMER

Withstands Switchgear Impulse Tests

by **ALBERT EWY**
Engineer in Charge
Switchgear Design
Allis-Chalmers Mfg. Co.

WHEN AUXILIARY POWER is used in high voltage metal-clad switchgear to operate the vital miscellaneous devices such as breaker solenoids, battery chargers, lights, space heaters, and the like, some means of obtaining this auxiliary power from the primary bus is necessary.

In the past, this requirement was often met by using either standard liquid-filled or dry-type distribution transformers connected directly to the primary bus. Usually, a complete unit was devoted to enclose the transformer, fuses, and the disconnecting means.

Standard construction in metal-clad switchgear provides a drawout carriage for potential transformers within a compartment of a metal-clad unit. These carriages are suitable for mounting three potential transformers. It was desirable that these carriages be used to mount a suitable control transformer. This would permit a standard unit to be equipped with either potential or control transformers, utilizing the unit enclosure as the enclosing case.

TYPICAL single-phase control transformer of this special design. **(FIGURE 1)**

Since these transformers were to be used in factory assembled, metal-clad switchgear, it was necessary that they be designed to meet NEMA Standards for metal-clad switchgear.

These design requirements include:

(1) Temperature rise of 50 C over an outside enclosure ambient of 40 C.

(2) One-minute dielectric tests of 19 kv for 5-kv rated equipment and 36 kv for 15-kv rated equipment.

(3) Impulse test of 60 kv for 5-kv rated equipment and 95 kv for 15-kv rated equipment.

A series of dry-type control transformers were designed to meet these requirements. Figure 1 shows a typical single-phase, 10-kva, 5-kv control transformer assembly of the special design, while Figure 2 shows a similar 10-kva, 15-kv unit. Each is mounted on a drawout carriage assembly together with primary fuses. A secondary breaker is arranged with a safety interlock so that the breaker must be open before the drawout carriage can be disconnected. This prevents load current from being interrupted on the primary disconnects, forming a very compact and safe arrangement.

New design is safe, convenient to use

When mounted in a compartment, all the features of safety that are found in drawout potential transformer assemblies used in metal-clad switchgear are included.

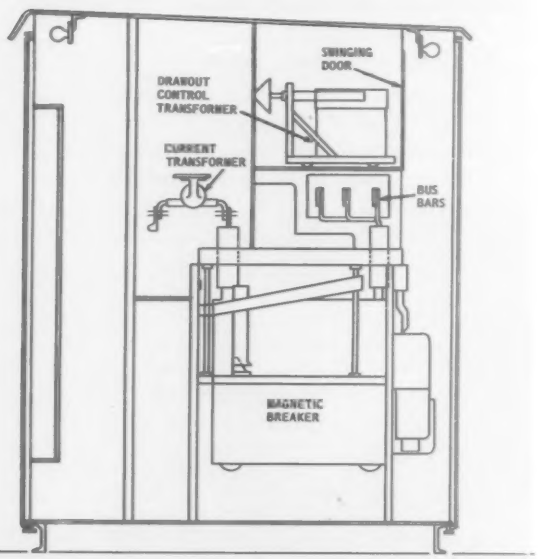
DRAWOUT CARRIAGE mounts primary fuse, control transformer with its secondary breaker and interlock. **(FIG. 2)**

Since the transformer and fuses are on the carriage, an operator cannot make contact with the transformer while it is energized, as could happen if the transformer was not part of the drawout carriage. The primary fuses may be removed with complete safety, since they are not accessible until the primary contacts have separated a safe distance. In addition, should there be trouble, the drawout assembly may be removed easily from the switchgear compartment and taken to a maintenance or test department for checking.

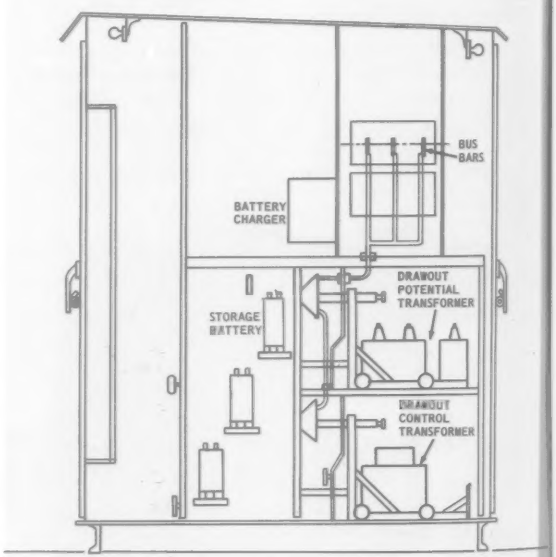
The control transformer and fuse assembly can fit in the same size compartment as a set of potential transformers. Figures 3 and 4 show how a control transformer can fit into a standard outdoor breaker unit or in a standard outdoor auxiliary unit. Figure 5 shows an oil-filled transformer used with drawout fuses. Two compartments of the auxiliary unit are required in this arrangement.

The maximum size control transformer that can be placed on a drawout carriage is 10 kva. This size is usually adequate to take care of the lighting, space heaters, breaker closing, and other miscellaneous auxiliary power requirements in a group of outdoor switchgear. Also the 10-kva transformer assembly will fit in the same size compartment as a potential transformer drawout assembly. This assists in standardizing metal-clad switchgear structures. Sizes above 10 kva are not used frequently, and because of their physical size and weight it is not desirable to place larger sizes on drawout carriages. When larger sizes are used, the assembly occupies two standard compartments. One compartment contains the transformer, while the other compartment is used for drawout fuses, as shown in Figure 5.

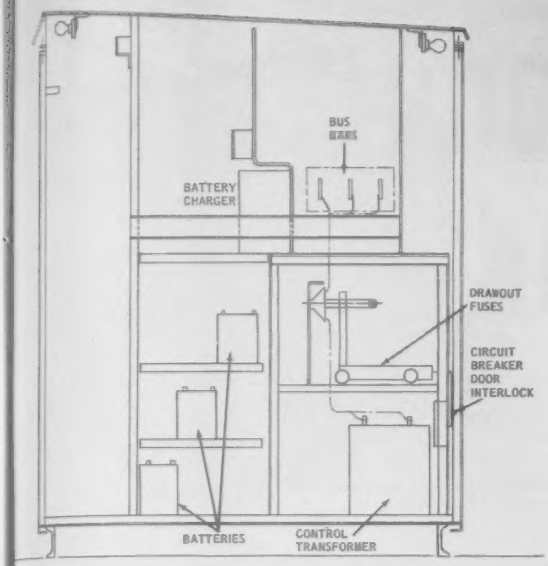
For reasons of economy, two series of control transformers were designed. One series has taps both 5 percent above and 5 percent below normal. The other series has no additional taps. The transformer without taps is more economical, yet satisfactory for the greatest percentage of applications.



LOCATION OF THE CONTROL TRANSFORMER in a standard outdoor breaker unit is indicated in this drawing. **(FIGURE 3)**



CONTROL TRANSFORMERS of this design, when placed in an outdoor auxiliary unit, are located as shown above. **(FIGURE 4)**



OIL-FILLED control transformers which are too large for drawout mounting are connected through drawout mounted fuses. **(FIGURE 5)**

Withstands switchgear dielectric tests

Figure 6 is a tabulation of the control transformers, listing the various ratings available. Dielectric strength tests specified by NEMA for metal-clad switchgear were applied to those special dry-type transformers. Figure 7 shows a test oscillogram of a 5-kv control transformer to which a ½-40 full voltage wave of 60 kv was applied, while Figure 8 shows the oscillogram of a 15-kv control transformer during ½-40 full voltage wave 95-kv test. These oscillograms indicate that dielectric tests can be made on metal-clad switchgear without removing control transformers of this design.

The tabulation in Figure 9 gives some comparative figures of the special designed dry-type transformer, standard dry-type transformer and the liquid-type transformer.

From the table it will be noted that the standard dry-type transformer has a much lower one-minute dielectric test, and no impulse voltage test is required by ASA Standards. The temperature rise is 5 C above the special dry-type transformer, but to this figure must be added the additional temperature rise incurred when the transformer is mounted in a metal-clad compartment.

The liquid-filled transformer has the same deficiency as the standard dry-type transformer insofar as the temperature rise is concerned. The one-minute dielectric test for the 15-kv rated transformer is 34 kv, while the special dry-type transformer is designed for 36 kv, the same value that applies to 15-kv rated metal-clad switchgear.

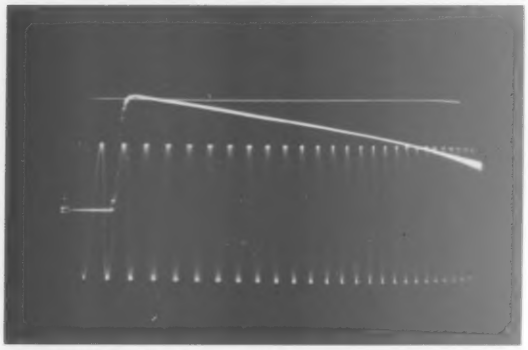
The special designed dry-type control transformer can be installed in metal-clad switchgear and all tests as called for in NEMA Standards applied. The transformers do not have to be disconnected while dielectric tests are applied to the switchgear. This is an advantage in field tests where personnel may not be as well informed about the conflicting standards in dielectric strength.

During the past few years, there has been a trend for the use of air circuit breakers rather than oil circuit breakers in metal-clad switchgear. This trend has been followed by an increased demand for dry-type control transformers in switchgear specifications. Usually, in the past a dry-type transformer as called for in the ASA

RATIO NORMAL VOLTAGE	Kva SIZE	CYCLES	INSULATION CLASS Kv	TAPS	
				Above Normal	Below Normal
2400-120/240	10	60	5.0	None	None
4200-120/240	10	60	5.0	None	None
4200-120/240	10	60	15.0	None	None
4800-120/240	10	60	15.0	None	None
7200-120/240	10	60	15.0	None	None
8400-120/240	10	60	15.0	None	None
12000-120/240	10	60	15.0	None	None
14400-120/240	10	60	15.0	None	None
2400-120/240	10	60	5.0	1-5%	1-5%
4200-120/240	10	60	5.0	1-5%	1-5%
4200-120/240	10	60	15.0	1-5%	1-5%
4800-120/240	10	60	15.0	1-5%	1-5%
7200-120/240	10	60	15.0	1-5%	1-5%
8400-120/240	10	60	15.0	1-5%	1-5%
12000-120/240	10	60	15.0	1-5%	1-5%
14000-120/240	10	60	15.0	1-5%	1-5%

CONTROL TRANSFORMERS that withstand switchgear impulse tests are built in these ratings and tap arrangements. **(FIGURE 6)**

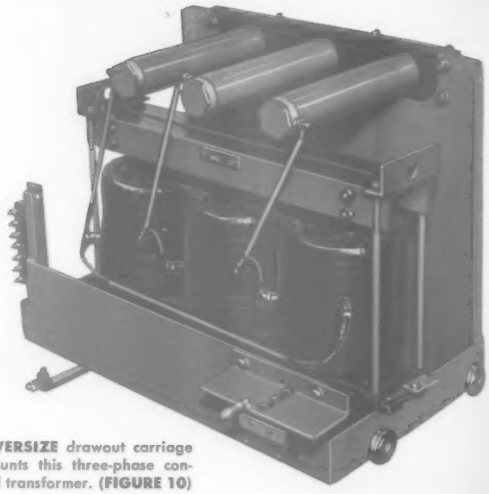
OSCILLOGRAM of 60-kv test on 5-kv control transformer. **(FIGURE 7)**



TEST VOLTAGE of 95-kv on a 15-kv control transformer produced this oscillogram. **(FIGURE 8)**

Standards has been supplied. These have the deficiencies as described in the above table when compared with NEMA Standards for metal-clad switchgear. The new, specially designed dry-type control transformers eliminate these shortcomings.

Figure 10 shows a 10-kva, 3-phase, 5-kv control transformer mounted on a drawout carriage. This was a special



OVERSIZE drawout carriage mounts this three-phase control transformer. **(FIGURE 10)**

drawout arrangement and is slightly larger than the drawout arrangement which mounts the single-phase 10-kva transformer. When several identical assemblies are required, special arrangements such as this can often be justified. In this case, valuable floor space savings were realized by the elimination of extra compartments.

These special transformers are designed for low impedance values. They may be used to draw several times their full-rated load for short periods of time with the minimum reduction of control voltage, as in breaker closing applications.

Special dry-type control transformers for metal-clad switchgear have definite advantages. They lend themselves to arrangements that have all the safety features expected of metal-clad switchgear standards, and they permit standardized assemblies which are compact and save space.

	VOLTAGE RATING	1 MINUTE TEST	½-40 WAVE FULL WAVE	TEMPERATURE RISE
SPECIALLY DESIGNED DRY-TYPE TRANS.	5 kv	19 kv	60 kv	50 C*
	15 kv	36 kv	95 kv	50 C*
DRY-TYPE TRANS. PER ASA STANDARDS	5 kv	12 kv	None Req'd.	80 C**
	15 kv	31 kv	None Req'd.	80 C**
LIQUID-FILLED TRANS. PER ASA STANDARDS	5 kv	19 kv	60 kv	50 C**
	15 kv	34 kv	95 kv	50 C**

* Values based on transformer mounted in a metal-clad compartment.
** Values based on transformer mounted in open air.

HIGH IMPULSE STRENGTH and low temperature rise typify these specially designed transformers. **(FIG. 9)**

Get Sound Bus Joints the Easy Way!

Neoprene Boot Simplifies Installation!

Only Allis-Chalmers Switchgear Uses This Method of Bus-Joint Construction

USERS OF ALLIS-CHALMERS Switchgear make or inspect bus joints in a fraction of the time and with none of the mess involved with any other switchgear. Best of all, it's a strong, corona-free joint meeting full impulse levels.

See how simple it is to make the bus joint. It's as easy in the field as it is in the factory. And note the construction details of these rigid joints.

This is but one of many advantages of Allis-Chalmers Switchgear. Get the full story from your nearby Allis-Chalmers district office. Or write Allis-Chalmers, Milwaukee 1, Wisconsin.

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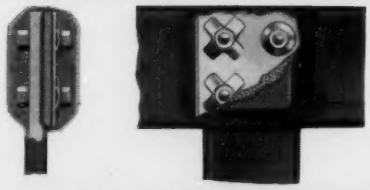


HERE'S HOW BUS JOINT IS MADE

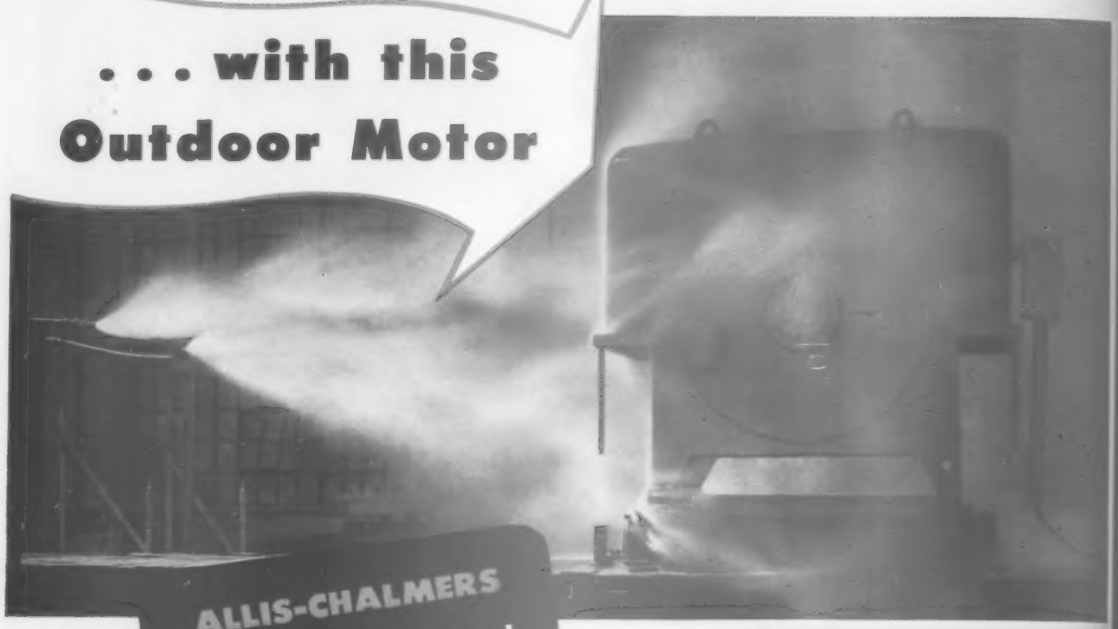
1. Bus bar connections are of round edge copper bar with at least 98 percent conductivity. Connections are silver plated to reduce contact resistance, and prevent overheating and oxidation. A combination of spring washers and lock washers assures proper contact of bars at all times. Slotted bolt holes permit expansion and contraction of bus... relieve strain on structure.

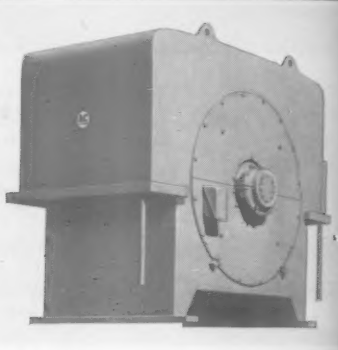
2. No-corona tape of copper mesh material is applied around the bolts and the overlapping joint. This eliminates corona in the connections and provides a uniform base for the Neoprene rubber boot. Special Neoprene boot with potential transformer tap is provided. A few turns of electrical tape hold the boot in place. No fuss, no muss, no liquid compounds.

ALLIS-CHALMERS

NO HOUSING PROBLEM

. . . with this Outdoor Motor





BEST WAY to solve a housing problem is to eliminate the need for housing! That's exactly what the Allis-Chalmers weather-protected motor does. It eliminates the need for a costly building . . . costly in added capital investment, costly in upkeep, and costly in extended construction time.

Proved by Special Tests

We know this weather-protected design can give you these savings . . . plus dependable performance . . . because we've tested it under extreme conditions.

Take the 900-hp, 435-rpm, 4160-volt motor shown above. While running at normal speed and voltage, it was deluged with water at rates up to 40 inches per hour — driven by winds up to 75 miles per hour. This was done repeatedly from all angles. But on inspection, no moisture was detected on the windings of this weather-protected motor.

And other tests checked its effectiveness in keeping out wind-driven fine sand.

Bulletin Describes Features

The construction features that provide this economical, super-splashproof performance are available in ratings for all major auxiliary drives. For more information, ask your nearby A-C representative for Bulletin 05R7874, or write to Allis-Chalmers, Milwaukee 1, Wisconsin. A-3907

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